2018

An evaluation of the Microsoft HoloLens for a manufacturing-guided assembly task

Melynda Hoover
Iowa State University

An evaluation of the Microsoft HoloLens for a manufacturing-guided assembly task

by

Melynda Hoover

A thesis submitted to the graduate faculty

in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

Co-Majors: Mechanical Engineering, Human Computer Interaction

Program of Study Committee:
Eliot Winer, Major Professor
Stephen Gilbert
James Oliver

Iowa State University

Ames, Iowa

2018

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

Page

ACKNOWLEDGMENTS

Thank you, Jon Schlueter, Stacy MacAllister, Jack Miller, Paul Easker, Peter Carlson, Maggie Iglesias Pena, Kaitlyn Ouverson, and Alec Ostrander, for being my comic relief, therapists, and sympathizers throughout this arduous process. To my professor and mentor, Eliot Winer, thank you for seeing my potential as a naïve freshman and for pushing me to take on new challenges. Derek Kreidler, thank you for being my rock and inspiring me with your love and work ethic. To my family, thank you for pushing me to explore and learn and for teaching me to be confident in my abilities. I could not have done this without the love and support of each and every one of you.

I would also like to thank my committee members, Stephen Gilbert, and James Oliver, for their guidance and support throughout the course of this research.

In addition, I would also like to thank my friends, colleagues, the department faculty and staff for making my time at Iowa State University a wonderful experience. I want to also offer my appreciation to those who were willing to participate in my user studies, without whom, this thesis would not have been possible.

ABSTRACT

Many studies have confirmed the benefits of using Augmented Reality (AR) work instructions over traditional digital or paper instructions, but few have compared the effects of different AR hardware for complex assembly tasks. For this research, previously published data using Desktop Model Based Instructions (MBI), Tablet MBI, and Tablet AR instructions were compared to new assembly data collected using AR instructions on the Microsoft HoloLens Head Mounted Display (HMD). Participants completed a mock wing assembly task, and measures like completion time, error count, Net Promoter Score, and qualitative feedback were recorded. The HoloLens condition yielded faster completion times than all other conditions. HoloLens users also had lower error rates than those who used the non-AR conditions. Despite the performance benefits of the HoloLens AR instructions, users of this condition reported lower net promoter scores than users of the Tablet AR instructions. The qualitative data showed that some users thought the HoloLens device was uncomfortable and that the tracking was not always exact. Although the user feedback favored the Tablet AR condition, the HoloLens condition resulted in significantly faster assembly times. As a result, it is recommended to use the HoloLens for complex guided assembly instructions with minor changes, such as allowing the user to toggle the AR instructions on and off at will. The results of this paper can help manufacturing stakeholders better understand the benefits of different AR technology for manual assembly tasks.

CHAPTER 1. INTRODUCTION

Purpose of Work

The goal of this research is to evaluate the effects of using AR instructions on a Microsoft HoloLens Head Mounted Display (HMD) for a guided assembly task. To this end, a user study was performed using a mock wing assembly task to evaluate the Microsoft HoloLens AR instructions. During the study, measures of assembly speed, errors, and Net Promoter Score (NPS) were recorded. This data was then compared to published data using three other types of assembly instructions: Desktop Model Based Instructions (MBI), Tablet MBI, and AR Tablet instructions. By examining this data, conclusions can be drawn regarding the relative advantages of using the Microsoft HoloLens to deliver AR work instructions in factory environments.

Motivation

Although a variety of industrial manufacturing processes are becoming automated, many products still require manual assembly by a human worker. This is especially true of assembly processes which change frequently or have custom feature options. This is because the cost of retooling can be high relative to the benefit of automation for these applications (Tang, Owen, Biocca, & Mou, 2003). For this to remain true, the benefit provided by human assemblers must continue to outweigh the cost of retooling automated equipment. One method of augmenting human performance in manual assembly tasks is the use of AR guided assembly instructions.

AR guided assembly instructions allow the user to view step-by-step instructions in real time while in the real assembly environment by superimposing computer-generated content over the user's view of the real world (Azuma, Baillot, & Behringer, 2001). This allows a user to see the necessary information to complete a job when and where it is most relevant, effectively eliminating the need to divide one's attention between the task and the instructions (Wickens, Gordon, Liu, & Lee, 1998). This instructional method can reduce the training time needed for new assembly tasks by giving instructions on the job. Additionally, AR instructions have been shown to reduce errors and assembly task times, ultimately resulting in significant cost savings for the manufacturer (Hou, Wang, & Truijens, 2015).

Despite the advantages of AR, which have been proven in many previous publications, few companies have been quick to adopt this technology for industrial manufacturing applications. But new commodity AR hardware like the Microsoft HoloLens, Daqri Smart Glasses, and the Meta 2 are making it easier than ever to implement AR technology. However, hardware advancements come with new questions surrounding the benefits of using AR for guided assembly tasks. Specifically, which hardware provides the most benefit when applied to realistic manual assembly tasks in a manufacturing environment?

This question can be broken down into two key components. The first is a comparison of modern AR hardware options. These include, but are not limited to, Hand-Held Displays (HHDs) like tablets and smartphones, and HMDs like the Microsoft HoloLens. By comparing new commercial hardware, this research will provide more updated information than previous research on AR guided assembly instructions. The second part of the problem is the application of these hardware to realistic assembly tasks. Previous AR hardware comparison studies have used simplified assembly tasks to investigate the benefits of AR devices (Funk, Kosch, Greenwald, & Schmidt, 2015). These include assemblies made from Lego bricks and simple wooden blocks. This poses a problem because the results of these studies cannot be easily applied to assemblies in a real factory environment which often involve more complex parts. Additionally, the tasks used for previous work are often tablet-top assemblies which do not account for the mobility of workers on a factory floor. By comparing several guided-assembly methods using a task with more complex parts and a larger work area, the results of this study will be more applicable to real-world manufacturing tasks.

By conducting a user study which combines both state of the art AR hardware, and a realistic assembly task, this research will help further understanding of the human performance benefits of AR guided assembly instructions. Additionally, this work will evaluate user attitudes towards current AR HMD technology, specifically the Microsoft HoloLens, for manual assembly applications. Ultimately, this updated work will provide more insight into how this technology can be applied to reduce costs in a manufacturing environment.

Thesis Organization

This research will be presented as follows. Chapter 2 will introduce background information which will provide a basic understanding of previous research in AR for guided assembly instructions as well as a summary of current AR hardware. Chapter 3 contains a journal article which was submitted to the Human Factors Prize Competition for publication in the journal *Human Factors* in June 2018. The paper describes the experimental methods used to conduct a comprehensive user study of four types of guided assembly instructions including the HoloLens HMD and a tablet-based AR HHD. The results and statistical methods used to evaluate them are also described in detail. Finally, Chapters 4 and 5 will explain the conclusions and suggestions for future work.

CHAPTER 2. BACKGROUND

The field of AR research as it pertains to guided assembly applications can be divided into five categories: 1) the benefits of AR work instructions, 2) user acceptance of AR technology, 3) development of AR guided assembly applications, 4) a summary of available AR hardware, and 5) previous comparisons of AR hardware. Each of these topics will be discussed in this section and will provide a necessary background to understand the contributions of this paper to the field of AR.

Benefits of AR Instructions

The concept of using AR to display work instructions was first proposed by Caudell and Mizell in 1992 (Caudell & Mizell, 1992). In their seminal paper, they suggested that a tracked, transparent head-mounted display could be used to provide dynamic graphical and text-based instructions to aircraft manufacturers, thereby reducing the need for physical design instructions like paper manuals. They predicted that further development and implementation of AR work instructions would result in improved efficiency and reduced costs associated with human performed manufacturing processes. Many researchers in the field of AR went on to confirm the predictions made by Caudell and Mizell. One example is the work by Hou et al. which compared the effects of using AR instructions as opposed to traditional isometric drawings for an assembly task. They found that the use of AR instructions led to 50% shorter assembly times, 50% fewer errors, and lower mental task loads. The authors also identified secondary benefits to AR instructions such as 50% reduction in labor costs and 66% reduction in rework costs due to assembly error rework

(Hou et al., 2015). These advantages of AR instructions will be described in greater detail in the following sub-sections.

Time Savings

Time savings is one of the most popularly cited benefits of AR instructions. This is a particularly important advantage to manufacturing because reducing assembly time can result in substantial cost savings and increased product output (Hou et al., 2015). Today, the most common method of providing work instructions for manual assembly tasks is via paper or digital 2D manuals. However, the manufacturing industry stands to gain substantial time savings by replacing these traditional methods with AR. Many studies in the field of AR find that users of the AR instructions complete manual assembly tasks significantly faster than those who use paper (Friedrich, 2002). For example, Baird and Barfield compared two different types of AR instructions to paper and digital 2D instructions for a motherboard assembly task (Baird & Barfield, 1999). The researchers found that both AR methods effectively reduced task completion times over the traditional paper and computer instructions. The authors also noted that the AR conditions in this study had some usability issues, including low resolution. Since this study, AR technology has improved, possibly resulting in even greater benefits to overall assembly speed.

However, some researchers have found that the benefits of AR work instructions are task dependent. One such theory is that AR instructions only make a difference in task completion time when the task in question is relatively difficult. This is because some assembly tasks are simple enough that they can be adequately depicted using traditional paper instructions. Wiedenmaier et al. investigated this topic using automotive assemblies of different complexity levels. (Wiedenmaier, Oehme, Schmidt, & Luczak, 2003). They found that the AR instructions only improved assembly times over paper manuals during the more difficult assembly task. This indicated that AR may not be beneficial for simple or repetitive tasks. Additionally, participants who received instructions from an expert instructor performed the assemblies slightly faster than those who used the AR instructions. However, using expert personnel to provide instructions and training can be expensive and the directions given by the expert instructor may not be consistent.

Other researchers have tried to identify specific types of assembly tasks which benefit from AR by investigating the effects of AR on specific steps of the assembly process. For example, Weaver et al. conducted a user study with twelve people comparing the use of four different instructional methods in a part picking task (Weaver, Baumann, Starner, Iben, & Lawo, 2010). They found that users performed the task fastest when using AR instructions, as opposed to a paper list, paper graphical instructions, and audio instructions. Similarly, Henderson and Feiner developed a tracked, head-mounted AR system which was used to guide the user's attention to the area of a military vehicle in need of servicing (Henderson & Feiner, 2009). Using AR, they reduced the time spent on locating parts in need of service as well as overall head movement in a confined environment.

AR instructions have also been found to have a positive effect on task completion times when used as a training tool. This application of AR instructions was studied by Boud et al. in 1999. They studied the effects of five different assembly training methods including AR, Virtual Reality (VR), and traditional 2D drawings (Boud, Haniff, Baber, & Steiner, 1999). After the training, users performed the assembly task from memory without assistance. They found that the AR condition yielded the fastest assembly times, followed by the VR conditions and then the conventional 2D drawings.

Error Reduction

Error reduction is another popular argument for employing AR work instructions because reducing errors in assembly tasks helps to decrease the output of defective product and cut rework time (Hou et al., 2015). Many studies to date have reported reductions in errors when using AR technology to present work instructions as opposed to traditional 2D instructions. For example, Tactić and Tešić created an AR maintenance instruction system to replace traditional paper check lists in a factory environment. They found that the AR instructions reduced the number of errors in the work procedures compared to the traditional method (Tatić & Tešić, 2017). Additionally, they found that the AR system helped increase occupational safety by preventing the user from skipping steps or completing them in an incorrect order. Baird and Barfield also studied the error rates of AR instruction users and those who used traditional instructions. They compared four different methods for presenting instructions for a motherboard assembly task: paper instructions, computer aided instructions, and two different AR HMDs (Baird & Barfield, 1999). Their study showed that both HMD methods yielded fewer errors than the non-AR methods. In a later study, Loch et al. developed an AR work station for a Lego assembly task. When tested against a video control group, users of the AR system performed the tasks with significantly fewer errors (Loch, Quint, & Brishtel, 2016). These studies and many more like them demonstrate how AR instructions can reduce assembly errors.

AR instructions can also be used to increase precision and accuracy in tasks such as welding (Echtler et al., 2004). A study by Doshi et al. investigated the use of AR for a spot welding task in an automotive factory environment. Based on an 8-sample user test, the authors determined that the AR system yielded significantly more accurate and precise spot welds than the traditional method (Doshi, Smith, Thomas, & Bouras, 2017). This study used the tracking capabilities of the AR equipment to help the welders more accurately align their tools for welding, ultimately improving the quality of the product and reducing rework time due to inaccurate welds.

Error reductions have also been found when using AR instructions for training applications. Gavish et al. assessed the effectiveness of AR training with respect to a control group using an instructional video. The study found that technicians who were trained using the AR system performed industrial maintenance and assembly tasks with fewer errors than their traditionally trained counterparts (Gavish, Gutiérrez, & Webel, 2013). Similarly, a 2014 study by Hořejší used a simple AR system as a training tool for novice users assembling plumbing pieces. The study showed that people who used the AR instructions while training learned to assemble the parts faster and in fewer attempts than their counter-parts who used only paper instructions (Hořejší, 2015). This work showed that AR instructions could potentially supplant traditional instructional methods as a beneficial tool for training. Additionally, training personnel using AR has the potential to decrease the frequency of errors later, on the factory floor, further reducing rework costs.

Other researchers have discovered some drawbacks of AR work instructions, specifically, an overreliance on the computer-generated material. Ockerman and Pritchett conducted early research on the use of an AR system for providing instructions in an aviation inspection task (Ockerman & Pritchett, 1998). They conducted a 15-person user study of three instructional conditions: no instructions (memory), AR text instructions, and

AR pictorial instructions. They observed that AR users tended to have an overreliance on the AR instructions which could result in errors if the computer-generated information is not completely accurate. This is especially applicable to modern AR which requires 3D tracking to place computer generated graphics in the scene. If the tracking is not accurate, the user may find it difficult to correctly interpret the instructions potentially resulting in assembly errors. Although technology has advanced since this 1998 study, whether modern AR hardware has completely solved this problem has yet to be fully tested.

Mental Workload

Another benefit of AR which is less widely studied is its potential to reduce mental workload on the user. Mental workload measures the mental strain that results from a particular task, in this case interpreting the assembly instructions (Wickens et al., 1998). One way in which AR instructions can reduce mental workload is by providing sequential task instructions, rather than using a paper manual. This reduces mental load by providing information when and where it is most necessary instead of forcing the user to recall the information or find it in a manual. Crescenzio et al. demonstrated this advantage with an AR system for checking the oil levels in a small aircraft (De Crescenzio et al., 2011). Their research showed that the AR system increased task efficiency when compared to paper instructions and reduced the mental workload on the maintenance personnel. Funk et al. also measured the mental workload of participants in an assembly related task and found similar results. They developed an AR system which used projection to direct the user in part picking tasks. They found that using the head-mounted projection AR system significantly decreased the cognitive load required for the task according to the NASA-TLX survey (Funk, Mayer, Nistor, & Schmidt, 2016). Studies like these show that AR instructions can not only improve human performance but reduce mental load on the user as well.

Collaboration

AR has also been investigated for its potential to allow team members to collaborate with one another while performing an assembly task. By adding a means of communication to the AR instructions, the user can ask clarifying questions or receive directions from other workers who are at a distance while on the job without interrupting the current task. Lamberti et al. (2014) assessed this very feature by implementing a remote expert system, allowing the user to communicate remotely with a skilled technician while performing the assembly task. They found that the AR system reduced errors during the assembly, and in the case of the remote expert system, also reduced the amount of time required to perform the task (Lamberti et al., 2014). Similarly, Abramovici et al. found favorable results using an AR system which allowed for the coordination of a two-person maintenance task (Abramovici, Wolf, Adwernat, & Neges, 2017). This research shows that AR technology can serve not only to provide instructions, but to connect people in the field as well, which can further augment human performance.

Limitations of AR

Despite all the advantages of AR, researchers have identified several limitations of the technology which could potentially detract from the benefits of AR instructions. One of the most cited limitations of AR technology is the need to improve 3D tracking (Ockerman & Pritchett, 1998). This limitation was emphasized by Nee and Ong in their 2013 survey of the AR manufacturing applications. They concluded that the speed of registration with the physical world needed to be improved in order to provide a more intuitive and effective experience for users (Nee & Ong, 2013). Another survey of AR in manufacturing, by Dini and Mura, commented on the formfactor and ergonomics of AR hardware, specifically HMDs. They suggested that AR applications in this industry could be improved with the development of more portable and comfortable AR HMDs (Dini & Mura, 2015). Despite advancements in AR technology, Palmarini et al. continued to cite limitations of AR hardware. They conducted a survey of 30 influential papers in the field of AR maintenance. From their research, they found that improvements in transparent HMD hardware, registration and tracking, and interaction techniques must be made in order for practical implementation to occur (Palmarini, Erkoyuncu, Roy, & Torabmostaedi, 2018). However, none of the papers included in this survey used newly released AR HMDs such as the Microsoft HoloLens to present AR work instructions. Therefore, further research using the HoloLens is necessary to understand if these limitations like these still pose a problem.

User Acceptance of AR Technology

AR technology marks a big change from widely accepted instructional methods like paper manuals and digital 2D instructions. Some users who are more risk adverse may reject this technology, especially if they don’t see the immediate benefit to themselves (Rogers, 2003). In 2001, Azuma et al. warned that social acceptance could be a limiting factor in the adoption of AR technology (Azuma et al., 2001). In 2005 Regenbracht et al. conducted a survey of ten AR papers in the aerospace and industrial fields. They concluded that AR still required maturation in hardware and social acceptance (Regenbracht, Baratoff, & Wilke, 2005). However, these conclusions were made during the early development of

AR technology. More recently, technologies like smartphones and tablets have proliferated in western society, paving the way for the adoption of AR technology.

Several researchers have studied user acceptance of AR technology in the context of AR work instructions with positive results. For example, Siegel and Bauer conducted a small-scale user study of six maintenance personnel who used AR instructions and a wearable computer to perform aircraft maintenance tasks (Siegel & Bauer, 1997). In post-task interviews, all the participants reported that they would be open to using a similar AR system to do their job in the future. This feedback was very promising for the future adoption of AR systems, especially considering the limitations of AR hardware at the time of this study. However, the small sample size in this study limited the validity of the results. More recently, Nilsson and Johansson conducted a study on the use of an optical see-through HMD for presenting medical equipment assembly instructions to nurses. Similarly to previous work, they found that the nurses were very accepting of this new method of instructions and found it easy to use (Nilsson & Johansson, 2007). Another study by Sanna et al. created an AR maintenance application on consumer devices such as tablets and smartphones. They also found that users reported positive opinions of the AR system (Sanna et al., 2015).

Some studies have received more mixed feedback from users who experienced AR hardware for the first time. For example, study participants who were asked to use AR instructions on a mobile device to perform maintenance procedures on an engine reported that they enjoyed using the instructions, but worried that the system might interrupt their current workflow (Aromaa, Aaltonen, Kaasinen, Elo, & Parkkinen, 2016). This result is one that is applicable to many potential AR applications, as users will need time to acclimate to the use of AR material. This may involve changing their work flow and even changing the work environment to use AR technology to its fullest potential.

Development of AR Interfaces

The design of AR interfaces is a field of research with few publications. However, creating intuitive AR applications is key to providing value for manufacturing and assembly tasks. One study recommended a plan for the authoring of AR assembly work instructions. The proposed method from this work involves subdividing tasks into the most simple steps and choosing the appropriate hardware based on the task in question (Chimienti, Iliano, Dassisti, Dini, & Failli, 2010). Although this serves as a good starting point for creating instructional content in AR, it does not address some of the interface design challenges of using AR hardware. These challenges include interface design, interaction techniques, and feedback to the user. Each of these topics will be discussed further in the following subsections.

Interface Design

AR hardware poses new problems for interface design because the interface must fuse computer-generated content with the real world. However, in order for the AR system to be effective, the visualized information must be carefully curated so as not to cause errors or confusion (Martinetti, Rajabalinejad, & Van Dongen, 2017). But few studies report on how to best present AR information to the user.

One of the biggest challenges for AR interfaces concerns how to direct the user's attention to the instructional content. This problem does not exist in 2D paper instructions, because the directions are not location dependent. With AR, the instructions are anchored to a point in the 3D world coordinate system. This means that the instructions may not be in the user’s field of view when dealing with large assemblies that require the user to travel around a work area. Therefore, it is necessary to direct the user’s attention to the instructions using navigational cues. Renner and Pfeiffer investigated methods for directing the user's attention in part picking and assembly tasks. They found that users felt the use of a series of 3D rings (the “tunnel” method) was less favorable than other techniques, like a 3D arrow (Renner & Pfeiffer, 2017). However, for this task, users were seated at a desk and did not have the freedom to walk around the space. Schwerdtfeger and Klinker compared three different methods for directing users’ attention in a larger work environment. They found that a "tunnel" style graphic was effective when users were not standing directly in front of the parts bins and had to search for the point of interest (Schwerdtfeger & Klinker, 2008). This study inspired the use of “tunnel” cues to direct the user’s attention in the AR instructions developed for this work.

Another challenge of designing AR instructional interfaces is how to most effectively present assembly information using 3D content. A study by Radkowski et al. in 2015 compared different methods of displaying 3D animations for AR instructions. Their research found that "concrete" instructions using 3D images of the parts moving into position yielded fewer errors than "abstract" AR instructions using arrows and text to indicate where the parts belong (Radkowski, Herrema, & Oliver, 2015). Researchers have also investigated the advantages of using sequential AR instructions over a single 3D schematic of the completed assembly. While 3D schematics may be effective for simple assemblies, larger assemblies with larger work areas may require more detailed step by step instructions (Chimienti et al., 2010; Khuong et al., 2014).

Interaction Techniques

Another challenge of AR interfaces is choosing an effective interaction technique. This is particularly important for manufacturing assembly tasks because environmental factors in a factory environment may affect the way in which a user interacts with the AR instructions. Researchers have investigated the use of voice commands as a technique for interacting with AR interfaces. This method is advantageous because it keeps the user's hands free during the assembly task. However, loud industrial environments may cause interference with auditory feedback and verbal input methods (Träskbäack & Haller, 2004). Despite this limitation, some researchers have continued to pursue this interaction technique for manual assembly tasks. A team from Siemens Corporate Research, integrated proximity sensors and speech recognition with an optical see-through AR display for more natural interaction between workers and machines. This combination of technologies allowed industrial maintenance personnel to access critical system information using voice activation by simply walking up to the equipment in question (Goose, Sudarsky, Xiang Zhang, & Navab, 2003). However, a formal research study was not conducted to determine the effectiveness of this technique on the factory floor.

Another novel method for interacting with AR technology is through natural user interfaces such as gesture controls. In an evaluation of AR publications in architecture, engineering, and constructions, Chi et al. recommended the use of natural user interfaces, such as gesture control, as an important area of future development in AR (Chi, 2013). By using gesture controls, users will be able to navigate through AR content in the field more quickly (Yeh, Tsai, & Kang, 2012). Although gestures can be helpful for triggering events in AR, fine object manipulation using gesture control is still a challenge. Wang et al. created an AR system which allows the user to manipulate virtual parts in AR using natural gesture recognition, however, this method can be computationally expensive and was limited to two finger gestures. (Wang, Ong, & Nee, 2016). Additionally, personal-protective equipment, such as work gloves, may interfere with gesture recognition.

Feedback

Feedback is also important aspect of intuitive AR instructions because it provides context and information to the user about how they are progressing through the instructions. One type of feedback that is important to AR work instructions is ensuring the user that the system has recognized their input. This is typically done using visual cues. However, Webel et al. tested haptic feedback as a method for providing this confirmation to users of an AR maintenance training application. They found that participants who used the haptic feedback AR system made fewer errors and had shorter completion times on the unaided task than those who were trained with instructional videos (Webel et al., 2013).

Another important type of feedback in assembly applications is verification. This type of feedback notifies the user of mistakes in their assembly. Westerfield et al. conducted a user study comparing the effects of traditional AR assembly training to an AR training module with the addition of an intelligent tutoring system for a motherboard assembly task. They found that the intelligent tutor, which provided feedback about the user's progress and tips for improvement, improved performance by 30% (Westerfield, Mitrovic, & Billinghurst, 2015). Mura et al. designed a method for identifying assembly errors using data from a force sensor integrated into a work bench. Using this information, the authors were able to improve the AR work instructions by providing error messages and additional instructions when necessary via optical AR glasses (Mura, Dini, & Failli, 2016). This feedback is especially useful in training situations where first-time accuracy is very important. However, error recognition is very difficult and computationally expensive to execute effectively in a dynamic factory environment.

AR Hardware

Several types of hardware are currently available for delivering AR work instructions to the user. These hardware options can be divided into five categories: HMDs, HHDs, stationary monitors, projectors, and smart glasses. This section will describe each of these categories as well as previous research on the benefits of each system. A table of the features of each type of AR hardware is provided (Table 1). Developers can then weigh the tradeoffs of features like these to predict which hardware will be most effective for the task at hand (Palmarini, 2017).

Table 1. Features of existing AR hardware.

	HMDs	HHDs	Monitors	Projectors	2D Smart Glasses
Mobile	X	X			X
Spatially Registered	X	X	X	X	
Hands Free	X		X	X	X

Head-Mounted Displays

One of the most iconic types of AR hardware available today are HMDs. HMDs are advantageous because they position the screen directly in the user's field of view. This creates a seamless transition between the real world and the computer-generated AR content, increasing the user's sense of presence in the mixed reality environment (Milgram, Takemura, Utsumi, & Kishino, 1995). HMDs can be further categorized into two groups: optical see-through displays, and video see-through displays (Ong, Yuan, & Nee, 2008).

Rolland and Fuchs compared the relative advantages of optical versus video see-through HMDs for AR hardware in medical applications. They noted that optical see-through AR displays offer an "unhindered" and "instantaneous" view of the real world, but they sometimes sacrifice AR field of view and accuracy of 3D registration. On the other hand, video see-through displays tend to have more accurate 3D spatial registration, however, these devices negatively affect hand-eye coordination (Rolland & Fuchs, 2000). This is likely due to discrepancies between eye placement and camera placement when using video see-through systems (Biocca & Rolland, 1998).

HMDs can also be advantageous to assembly applications because they allow the user to view spatially registered, 3D instructions while keeping their hands free for manual tasks. In a study by Syberfeldt et al., qualitative data was gathered from factory workers using four different AR systems, including an optical see-through HMD. The users responded favorably to the optical see-through display because it kept their hands free and allowed then to maintain a natural view of the real world. However, participants also reported that the device was difficult to wear with glasses and it felt heavy after wearing for a long period of time (Syberfeldt, Holm, Danielsson, Wang, & Brewster, 2016). Since this study was conducted, new HMD hardware such as the Microsoft HoloLens, Daqri Smart Glasses, and the Meta 2 have come to market. Devices like these have a smaller form factor which may provide for a more comfortable user experience than reported in earlier studies. This study will further investigate users’ opinions on using new HMD AR hardware for viewing assembly instructions.

Hand-Held Displays

HHDs are a category of AR hardware that includes mobile devices such as smartphones and tablets. To display AR on an HHD, computer-generated graphics are overlaid onto real-time video from the device's camera. This type of AR creates a "window" through which the user can see the AR content (Azuma et al., 2001). HHD systems for viewing AR work instructions have been well studied because of the low cost and high availability of this type of hardware. Many researchers have demonstrated the positive impact of this technology on human performance (Webel et al., 2013). In studies where tablet AR instructions were compared to traditional paper manuals, the HHD AR option has led to decreases in time and errors, and subjects reported a more positive user experience (Sanna et al., 2015). These devices are commonly used to present AR instructions because they are inexpensive and widely available. However, some users disliked that they had to either hold or constantly move the tablet around the room (Syberfeldt et al., 2016). Others have reported positive opinions of the system, but hand concerns with how the tablet might interrupt their workflow. This study was limited by the small sample size of the study (Aromaa et al., 2016). This problem can be mitigated by providing the user with a mobile stand for the HHD, however, the mobility of the device is still less than that of an HMD.

Monitors

Television screens and computer monitors are another method of presenting AR instructions. Monitors can provide similar AR content as HHDs, however, the screen remains stationary. This can be effective in smaller, benchtop work environments where mobility is not a priority (Loch et al., 2016). In a study by Echtler et al., a monitor-based

AR display was used for aiding in the welding of a vehicle body. In a small case study, they found that the AR system increased the welding efficiency of the workers (Echtler et al., 2004). Similarly, Fiorentino et al. compared the use of registered AR work instructions displayed on a large monitor to paper instructions for a motor assembly. The researchers found that the AR delivery method improved both task completion times and error rates (Fiorentino, Uva, Gattullo, Debernardis, & Monno, 2014). Although monitor AR work instructions keep the user's hands free, they may require the users to travel back and forth between the assembly and the monitor, especially if the task requires them to travel around a larger work environment. This makes monitor AR systems more suitable for small, localized assemblies.

Projectors

Projector AR methods cast images directly onto the work surface in order to provide spatially registered instructions to the user. This requires a projector to be mounted directly above or in front of the work surface. It also means the projected instructions are only displayed on one plane of the assembly making this method more feasible for relatively flat assemblies. Additionally, like monitors, projectors are generally a stationary means of providing AR work instructions making them useful for small assemblies or those which require little movement (Rodriguez, Quint, Gorecky, Romero, & Siller, 2015). However, in some cases, multiple projectors can be used to provide AR instructions for a large or complex assembly.

Despite some of the limitations of projection AR systems, they have been found to improve performance on assembly tasks over traditional instruction methods. Uva et al. studied found that participants who used an AR projection system to complete a maintenance task on a motorbike engine made significantly fewer errors and completed the task faster that those who only used a paper manual (Uva et al., 2017). Another study by Zhou et al. created a projector AR system to aide in the inspection of spot welds in the automotive manufacturing industry (Zhou et al., 2012). Finally, Marner et al. compared a spatial AR displayed using a projector to traditional instructions presented on a monitor. The found that the AR projection method significantly decreased task duration, head movement, and errors for a sequential button pressing task (Marner, Irlitti, & Thomas, 2013).

2D Smart Glasses

Another technology which has been explored for guided assembly applications is early smart glasses. Devices in this category, such as Google Glass, are different from optical see-through HMDs because they can only render 2D content. In addition, the virtual graphics are not updated in real time or registered with the real environment, which is an important feature for the understanding of assembly tasks in AR (Azuma, 1997). Despite these disadvantages, researchers have found that early versions of smart glasses can still benefit human performance in guided assembly tasks when compared to traditional methods (Baird & Barfield, 1999; Zheng et al., 2015). This is because the information is still displayed in the user's natural field of view, reducing the load on the user's working memory and helping them associate information with objects in the real world (Neumann & Majoros, 1998; Wickens et al., 1998).

Previous Comparisons of AR Hardware

Since AR technology became available, researchers have been attempting to quantify the advantages of different types of AR instructions over traditional assembly work instructions like paper manuals and 2D digital instructions (Tang et al., 2003). Fewer researchers have studied the performance effects of different AR hardware. Many of the published works on this subject used simplified assembly tasks such as Lego brick assemblies (Funk et al., 2015). Simple tasks like this have been used to evaluate many types of AR hardware including smartphones, tablets, HMDs, and projection (Blattgerste, Strenge, Renner, Pfeiffer, & Essig, 2017; Funk, Kosch, & Schmidt, 2016). Though these studies showed some advantages to using the HoloLens over HHDs for simple tabletop assemblies, more research is needed to understand the benefits of this technology in large-scale assemblies with a mobile user. Publications which compare the use of different AR hardware for more realistic assembly situations are rarer. One of the few studies of dissimilar AR hardware in a complex assembly task did show performance advantages to using AR HMDs, however, the HMD used in this study is now obsolete (Syberfeldt, Danielsson, & Holm, 2015). Since then, new hardware like the Microsoft HoloLens, Daqri Smart Glasses, and Meta 2 have been released.

Research Questions

With the newfound availability of commodity AR hardware, there is a growing need to understand the tradeoffs between different AR technologies. By adapting previous work to include new commercial hardware like the Microsoft HoloLens, this research will help build understanding of the impact this device has on human performance. This is important because HMDs like the Microsoft HoloLens represents a marked change in HMD technology that is not yet fully understood by the AR and manufacturing communities. In addition, by using a more realistic, large-scale assembly task, this research will provide more insight into the benefits of modern AR technology for use in industry. Therefore, this research will address the following questions:

1. *Does the use of AR instructions delivered on an optical see-through HMD, like the Microsoft HoloLens, improve human performance on a realistic manual assembly task?*

   AR work instructions have been shown to improve human performance in terms of task duration and errors. But modern HMDs, like the HoloLens, present an opportunity to further augment performance by providing better mobility, and more accurate tracking within a smaller form factor than previous AR HMDs.

2. *Will users prefer the Microsoft HoloLens AR instructions over other guided assembly instruction delivery methods?*

   Despite advantages to human performance, a large factor in the adoption of new technology is user acceptance. With the introduction of novel computing devices, like the Microsoft HoloLens, it is important to understand the user's perception of the product and how it can be changed to create a more effective user experience.

CHAPTER 3. MEASURING THE PERFORMANCE IMPACT OF USING THE MICROSOFT HOLOLENS TO PROVIDE ASSEMBLY WORK INSTRUCTIONS

Abstract

Objective: The human performance benefits of four types of guided assembly instructions, including the Microsoft HoloLens, were analyzed in the context of a realistic assembly task.

Background: Several studies have confirmed the benefits of using Augmented Reality (AR) work instructions over traditional digital or paper instructions, but few have compared the effects of different AR hardware, including head mounted displays, for complex assembly tasks.

Method: Participants completed a mock wing assembly task using the Microsoft HoloLens, and completion time, error count, and Net Promoter Score (NPS) were recorded. This data was compared to data from previous studies, which employed Desktop Model Based Instructions (MBI), Tablet MBI, and Tablet AR instructions for the same task.

Results: The use of HoloLens AR instructions led to time savings of 16% over the Tablet AR instructions. HoloLens users also had lower error rates than non-AR users. Despite the performance benefits of the HoloLens AR instructions, this condition had a lower NPS than the Tablet AR group. The qualitative data showed that some users thought the HoloLens device was uncomfortable and that the tracking was not always exact.

Conclusion: Although the users favored the Tablet AR condition, the HoloLens condition had significantly faster assembly times. The authors recommend using the HoloLens for complex guided assembly instructions with minor changes, such as allowing the user to toggle the AR instructions on and off at will.

Application: The results of this paper can help manufacturing stakeholders understand the benefits of different AR technology for manual assembly tasks.

Introduction

The applications of Augmented Reality (AR) are diverse, ranging from locating restaurant options on a busy street (Liao & Humphreys, 2015) to delivering detailed instructions on an aircraft assembly line (Boeing, 2018). But one of the most frequently studied applications of AR is guided assembly tasks (Palmarini, Erkoyuncu, Roy, & Torabmostaedi, 2018). Publications in this field are numerous and span a variety of industries such as aerospace (Caudell & Mizell, 1992), automotive (Echtler et al., 2004; Wiedenmaier, Oehme, Schmidt, & Luczak, 2003), and even healthcare (Nilsson & Johansson, 2007). This area has garnered a lot of attention because of the proven benefits of AR to human performance in manual assembly tasks. These benefits have been demonstrated through several studies, some of which have shown AR can improve task completion times by up to 50% (Henderson & Feiner, 2011). Other studies have demonstrated that AR instructions can significantly reduce errors in manual assembly tasks (Richardson et al., 2014; Tang, Owen, Biocca, & Mou, 2003; Tatić & Tešić, 2017).

Studies like these prove that AR is a powerful tool for quickly providing people with important information about their surroundings. This is made possible by superimposing computer-generated information over the user’s view of the real world. Additionally, full-featured AR also includes 3D graphics that are spatially registered with the environment and updated in real-time (Ronald Azuma, 1997). AR can be viewed in a variety of ways, each with its own advantages and limitations.

Until recently, the most accessible option for viewing AR instructions was via Hand-Held Devices (HHDs) like tablets or smartphones. To display AR on an HHD, computer-generated graphics are overlaid onto real-time video from the device’s camera.

This type of AR creates a “window” through which the user can see the AR content (Azuma, Baillot, & Behringer, 2001). HHD systems for viewing AR work instructions have been well studied because of the low cost and high availability of this type of hardware. Many researchers have demonstrated the positive impact of this technology on human performance (Boud, Haniff, Baber, & Steiner, 1999; Henderson & Feiner, 2009; Hou, Wang, & Truijens, 2015). In studies where tablet AR instructions were compared to traditional paper manuals, the HHD AR option has led to decreases in time and errors, and subjects reported a more positive user experience (Sanna et al., 2015).

Other researchers have studied the use of hands-free AR instructions via Head-Mounted Displays (HMDs). This can be done in one of two ways: by showing graphics overlaid on top of a real-time video of the user’s surroundings (video see-through AR), or by projecting the graphics onto a transparent lens (optical see-through AR) (Nee, Ong, Chryssolouris, & Mourtzis, 2012). However, video see-through HMDs are not well-suited to providing guided assembly instructions because they can negatively impact depth perception and hand-eye coordination (Biocca & Rolland, 1998). Additionally, video see-through HMDs are more likely to cause simulator sickness than optical see-through HMDs (Cuervo & Eduardo, 2017).

One of the earliest examples of an optical see-through HMD was developed by Feiner et al. in 1993. However this hardware, like others of its time, had several limitations such as portability, field of view, and resolution (Feiner, Macintyre, & Seligmann, 1993). Despite the constraints of early HMDs, researchers still found them beneficial for delivering AR work instructions (Henderson & Feiner, 2009). Studies found that even early HMDs could increase efficiency and decrease mental work load for subjects performing assembly tasks (De Crescenzio et al., 2011). But until recently, optical see-through systems were difficult to implement due to the lack of commodity hardware on the market. New HMD hardware options like the Microsoft Hololens, Daqri Smart Glasses, and Meta 2 have made AR development for optical see-through displays more feasible ("DAQRI Smart Glasses," 2018, "Meta Augmented Reality," 2017; Microsoft, 2018). These devices allow a developer to create content quickly using tools such as Unity 3D (Unity Technologies, n.d.). During the development phase of this study, the Microsoft HoloLens was identified as the ideal hardware for this work because of its relatively low cost, high availability, large amount of supporting development documentation and integrated tracking, making it ideal for large-scale assembly applications (Microsoft, 2018).

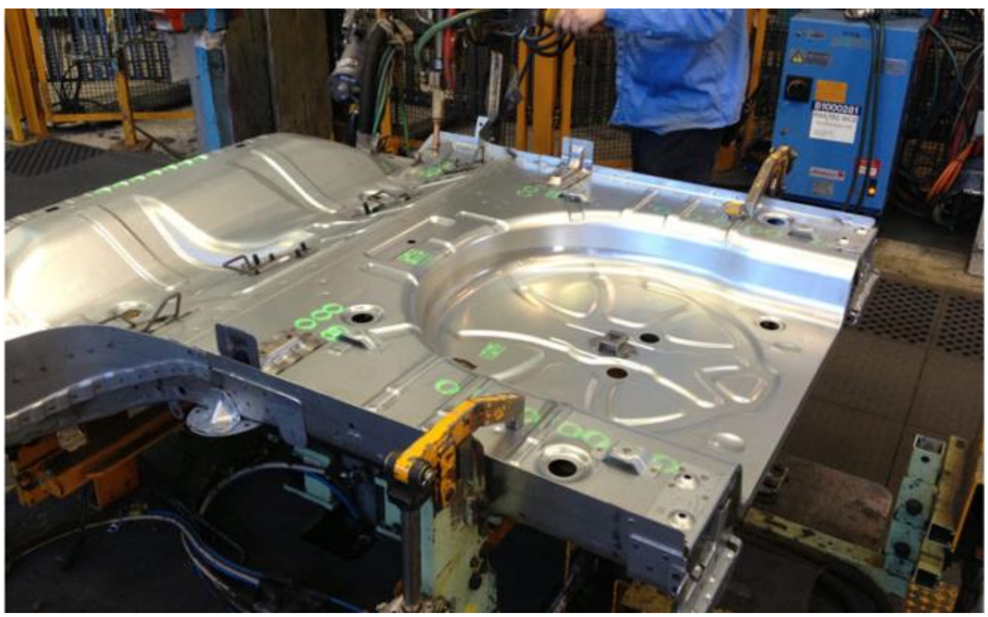

Figure 1. Example of projection AR in automotive welding task. Reprinted from "Use of projector based augmented reality to improve manual spot-welding precision and accuracy for automotive manufacturing," by A. Doshi, R. T. Smith, B. H. Thomas, and C. Bouras, 2017, *The International Journal of Advanced Manufacturing Technology*, 89(5-8), p. 1288. Copyright 2017 by Springer.

Although HMDs and HHDs are the most frequently studied hardware for presenting AR instructions, other methods of displaying AR have been tested as well, including stationary monitors (Hou et al., 2015; Loch, Quint, & Brishtel, 2016) and projectors, which shine light onto the surface of an assembly to indicate where to perform an assembly action (Figure 1) (Uva et al., 2017). While these methods work well in small, isolated work areas, they are not easily adaptable to larger, dynamic work environments because of their immobility. This makes them a less desirable option for large-scale manufacturing and assembly tasks.

Early versions of smart glasses, which rendered only 2D content, have also been explored for guided assembly applications. Devices in this category, such as Google Glass, are different from optical see-through HMDs because the virtual graphics are not updated in real time or registered with the real environment, which is an important feature for the understanding of assembly tasks in AR (Ronald Azuma, 1997). However, researchers have still found that these early smart glasses can still benefit human performance in guided assembly tasks (Baird & Barfield, 1999; Zheng et al., 2015). This is because the information is displayed in the user's natural field of view, reducing the load on the user's working memory and helping them associate information with objects in the real world (Neumann & Majoros, 1998; Wickens, Gordon, Liu, & Lee, 1998). Similarly, non-registered 2D instructions can be displayed on an HHDs. This method has not been shown to provide advantages over paper instructions (Funk, Kosch, & Schmidt, 2016). However, 2D tablet instructions have been shown to reduce assembly time and errors compared to 2D instructions displayed on a desktop computer (Richardson et al., 2014).

Since AR technology became available, researchers have been attempting to quantify the advantages of AR instructions over traditional assembly instructions (Tang et al., 2003). But fewer researchers have studied the performance effects of using different types of AR hardware to deliver work instructions. Many of the existing work on this subject used simplified assembly tasks such as Lego brick assemblies (Funk, Kosch, Greenwald, & Schmidt, 2015). These simple tasks have been used to evaluate many types of AR hardware including smartphones, tablets, HMDs, and projectors (Blattgerste, Strenge, Renner, Pfeiffer, & Essig, 2017; Funk et al., 2016). Though these studies showed some advantages of using HMDs over HHDs for simple tabletop assemblies, more research is needed to understand the benefits of this technology in large-scale assemblies. Publications that compare AR hardware for more realistic assembly tasks are scarce. One of the few studies of dissimilar AR hardware for a complex assembly task did show performance advantages to using AR HMDs, however, the HMD used in this study is now obsolete (Syberfeldt, Danielsson, & Holm, 2015).

With the newfound availability of commodity AR hardware, there is a growing need to understand the tradeoffs between different AR technologies. By adapting previous work to include new commercial hardware like the Microsoft HoloLens, this research will help build understanding of the impact this device has on human performance. This is important because the Microsoft HoloLens, and its contemporaries, represent a marked change in HMD technology that is not yet fully understood by the AR and manufacturing communities. In addition, by using a more realistic, large-scale assembly task, this research will provide more insight into the benefits of modern AR technology for use in industry.

Methods

The following section describes the task, independent variable conditions, procedure, and measures used to evaluate the Microsoft HoloLens in this study.

Task

A mock aircraft wing assembly task was used to evaluate the four types of guided assembly instructions. During the task, the instructions directed the user to identify and retrieve parts from the parts table and fastener bins, align parts on the wing table, and assemble the parts using metal fasteners. The parts table, fastener bins, and wing table were positioned as shown in Figure 2. Participants used wooden parts, metal fasteners, and wires to assemble the mock wing shown in Figure 3. No tools were required for this assembly, as all the fasteners could be hand tightened. This reduced the variability of the results due to previous experience with tools.

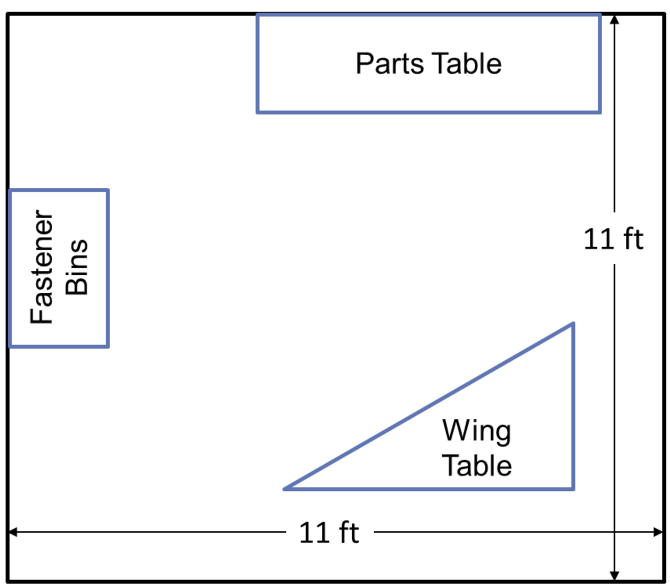

Figure 2. Task environment layout.

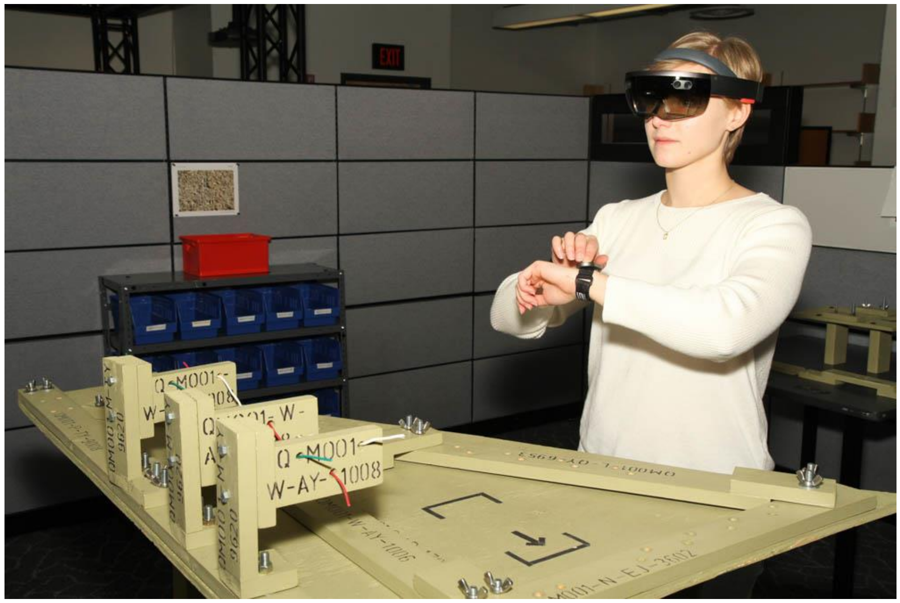

Figure 3. HoloLens HMD with Bluetooth clicker and completed mock wing assembly.

Conditions

The goal of this work was to investigate the possible advantages of using AR instructions on the Microsoft HoloLens for a realistic guided assembly application. To perform this evaluation, assembly instructions were developed for the HoloLens and compared to previously published work that studied the effects of 2D model-based instructions (MBI) on a desktop computer, MBI tablet instructions, and AR tablet instructions. The four different instructional conditions that were used for this comparison are described in the following subsections.

Desktop MBI. The desktop condition did not use AR, but instead consisted of a series of static figures and text presented as a PDF, which is typical of 2D electronic instructions used on shop floors today (Richardson et al., 2014). Users navigated through the steps one at a time by pressing back and next buttons on a touch screen desktop display (Figure 4).

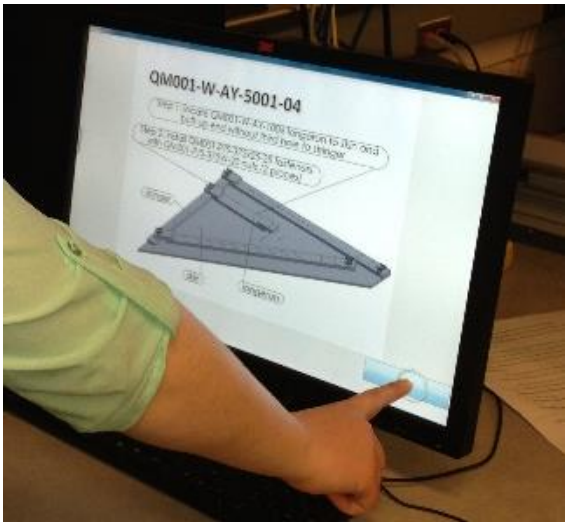

Figure 4. Desktop MBI condition using a touchscreen monitor.

Figure 5. Tablet MBI condition.

Mobile Tablet MBI. The Mobile Tablet MBI condition did not present the user with AR instructions. Instead, it used 2D images, text instructions, and a touch-enabled display to navigate between assembly steps (Figure 4), similar to the Desktop MBI instructions (Richardson et al., 2014). However, the tablet was mounted on a rolling stand with a pivoting arm, which freed up the user's hands for the manual assembly tasks, and let the user take the instructions with them as they moved to different areas in the work area.

Mobile Tablet AR. The mobile tablet AR condition used the same tablet and stand as the mobile tablet MBI. However, AR content in the form of dynamic 3D animations and text instructions were overlaid onto a live webcam video (Figure 6). These animations showed the part manipulations required to complete each step of the assembly. Users of this system navigated between steps using a touchscreen interface. Additionally, the AR instructions used a tunnel of yellow gates to guide the user to the necessary location for each step of the assembly (Figure 7) (MacAllister et al., 2017). An infrared Vicon camera system and reflective markers were used for tracking the position and orientation of the tablet and the subject during the task. This information was used to correctly position the virtual images in the scene.

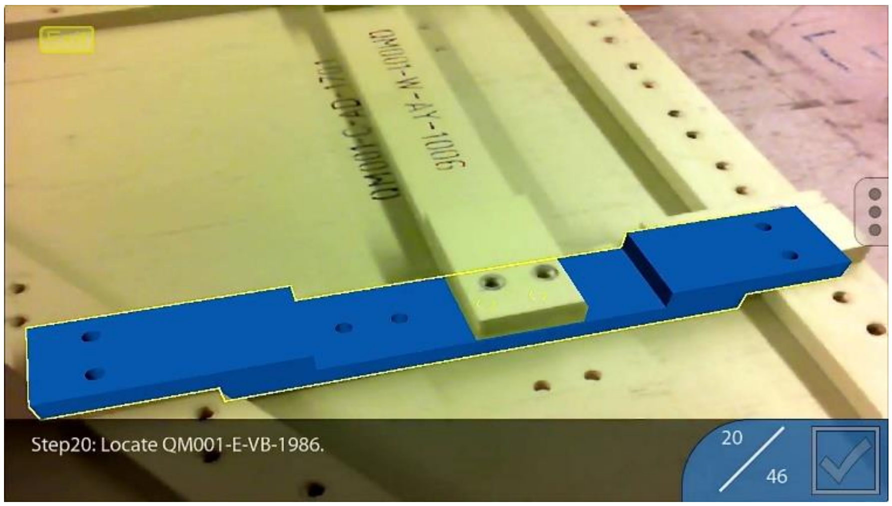

Figure 6. Screenshot of Tablet AR application with part assembly cue.

Figure 7. Screenshot of tunnel navigation shown on the AR tablet.

HoloLens AR. The interface and interaction development for the HoloLens assembly application was created using Unity 3D and the HoloToolkit, which has since been replaced by the Microsoft MixedRealityToolkit (Microsoft, n.d.). The HoloLens AR application used the same interface elements as the mobile tablet AR condition whenever possible. However, the use of an HMD required different interaction techniques. Users interacted with the AR interface by gazing at the target and then activating a Bluetooth clicker attached to their non-dominant wrist as shown in Figure 3. This kept the user's hands free for assembly tasks. Other interaction techniques such as gestures and voice commands were not selected because they are not always feasible in a factory environment (Träskbäack & Haller, 2004). The HoloLens has its own native tracking system, which was paired with Vuforia to enable 2D image tracking. Two image targets were placed on the walls and used to initialize the position of the HoloLens in the environment. When the image targets were not in the HoloLens field of view, the device's inertial measurement unit was used to determine its position relative to the rendered AR content. A short calibration procedure allowed the researcher to match the location of the AR content to the real objects in the work cell. This initial calibration process ensured that the tracking was accurate and reduced tracking errors during the study. Additionally, when the user put the HoloLens on, they adjusted the headset until four markers came into view. These marked the edges of the HoloLens field of view and ensured that the user was seeing all of the AR content.

Procedure

The same task and procedure was used in previously published work to gather data for the Desktop MBI, Tablet MBI, and Tablet AR conditions, as well as for new the

HoloLens AR condition (MacAllister et al., 2017; Richardson et al., 2014). The entire study took two hours to complete. First, the participant was asked to fill out a demographics survey. Then, the participant was instructed on how to use the assembly instruction hardware. During the practice assembly task, the participant was encouraged to ask questions to acclimate themselves to the environment and the work instructions. Next, the participant was given 45 minutes to complete Trial 1 of the mock wing assembly. During the trial, the participant was instructed not to ask questions. After the first trial of the wing assembly task was completed, the participant took a paper folding test to measure of spatial-thinking ability. During this test, the researcher recorded errors in the assembly and then disassembled the mock wing. Then, the participant performed Trial 2 of the same wing assembly task. At the end of the study, the participant completed a post-task questionnaire, which asked them to report on their experience using the assembly instructions.

Measures

Three quantitative measures were investigated during the study: accuracy, efficiency, and promotability. The first metric was the number of errors made at the end of each trial. This included misplaced, missing, extra, and incorrect parts. The next metric was the time required for the participant to complete each trial. Lastly, the net promoter score (NPS) was recorded. For this measure, a five-point scale was used to record a response to the statement “I would recommend work instructions like this to a friend” with 1 representing disagreement, and 5 representing agreement with the statement. Qualitative measures, in the form of written feedback, were used to understand the user’s experience and overall opinion of the HoloLens instructions. The two free-response questions ask for feedback on the user’s chosen NPS score, and their general feedback about the system.

Results

After the study was completed, time, errors, NPS, and qualitative data were compared between the four conditions. Before inferential statistics were performed, a Shapiro-Wilk test was used to determine normality. Most of the data sets violated the normality assumptions required for parametric tests such as an analysis of variance. Because of this violation, non-parametric tests like the Kruskal-Wallis test were used to calculate the difference in medians between the conditions. Using non-parametric tests also minimized the effects of outlying data points on the calculations.

Descriptive Statistics

In total, 103 samples were analyzed in this study. The distribution of participants among the four conditions was as follows: 13 desktop MBI participants, 15 tablet MBI participants, 40 tablet AR participants, and 35 HoloLens AR participants. Data for the Desktop and Tablet MBI conditions was taken from a previous study by Richardson et al. (2014). The Tablet AR data was aggregated from two previous studies which used the same mobile tablet AR application (Hoover et al., 2016; Macallister, Gilbert, Holub, Winer, & Davies, 2016). previously published data used for the Desktop and Tablet MBI conditions had smaller sample sizes than the two AR conditions, and could not be easily replicated due to the age of the system. More samples were available for the Tablet AR condition, since this data was collected for two different studies. However, despite the differences in sample sizes, statistically significant differences in performance measures were still found.

The demographics data showed that more men (72%) participated in the study than women (28%). Participants also reported their field of study in the demographics survey. Most of the participants were recruited from the Engineering College at Iowa State

University. Therefore, a large majority of student reported completion or progress towards a mechanical engineering degree (47%), or other type of engineering degree (32%), while only 21% were not pursuing any kind of engineering degree. This group was chosen because they were somewhat representative of typical assembly personnel, in terms of demographics and skills

Errors

For Trial 1, a Kruskal-Wallis test was conducted to determine if there were differences in the number of errors made by users of the four different instructional conditions: "Desktop MBI" (n=13), "Tablet MBI" (n=15), "Tablet AR" (n=40), and "HoloLens AR" (n=35). Visual inspection of the box plots of the Trial 1 errors in Figure 8 show that the four groups had similar distributions. Median error counts were statistically significantly different between the instructional groups, $\chi^2(3) = 30.670$, $p < .0005$. Subsequently, a pairwise comparison using Dunn's procedure and a Bonferroni correction for multiple comparisons was used to determine which groups had differences that were statistically significantly from one another. This post hoc test revealed that there was a significant difference between the median errors for the HoloLens AR (1.0) and the Tablet MBI (Mdn = 3.0) (p = .029) and the HoloLens and Desktop MBI (Mdn = 7.0) (p < .0005). The pairwise comparison also showed significant difference between the tablet AR condition (Mdn = 1.0) and Desktop MBI (Mdn = 7.0) (p < .0005).

Similar results were found for the Trial 2 data, which can be seen in the box plots in Figure 9. The boxplots again showed that the four groups had similar distributions. The Kruskal-Wallis test found that there was a significant difference between the number of

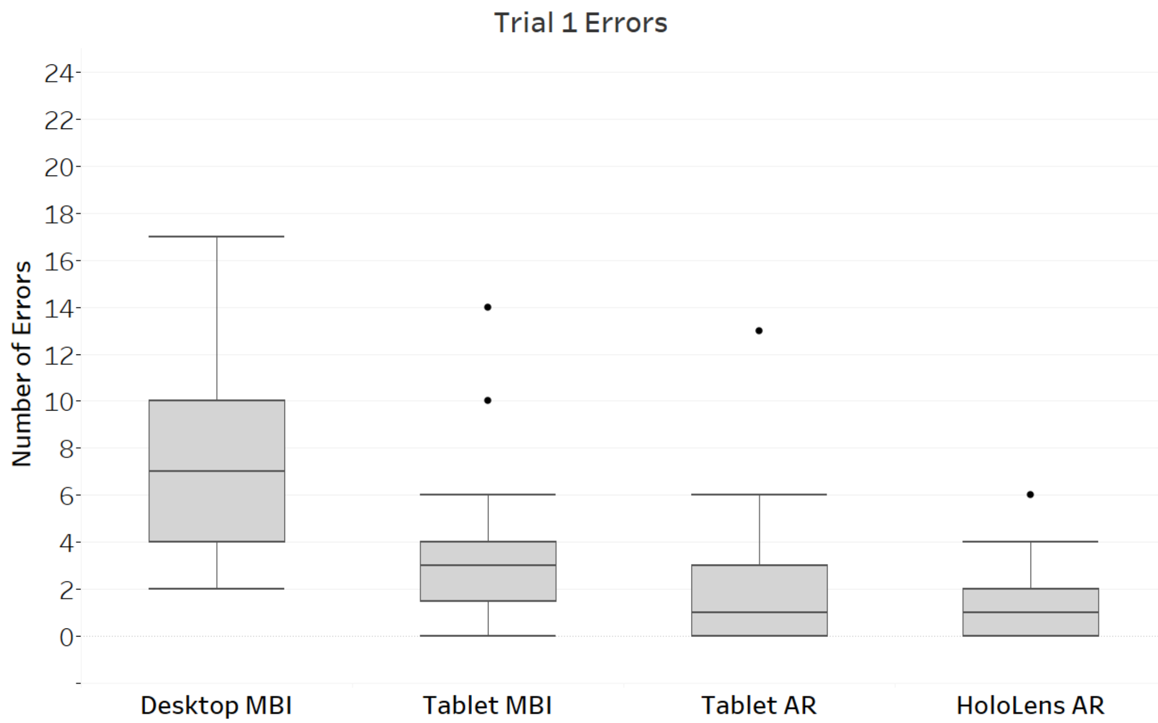

Figure 8. Bar charts of Trial 1 errors.

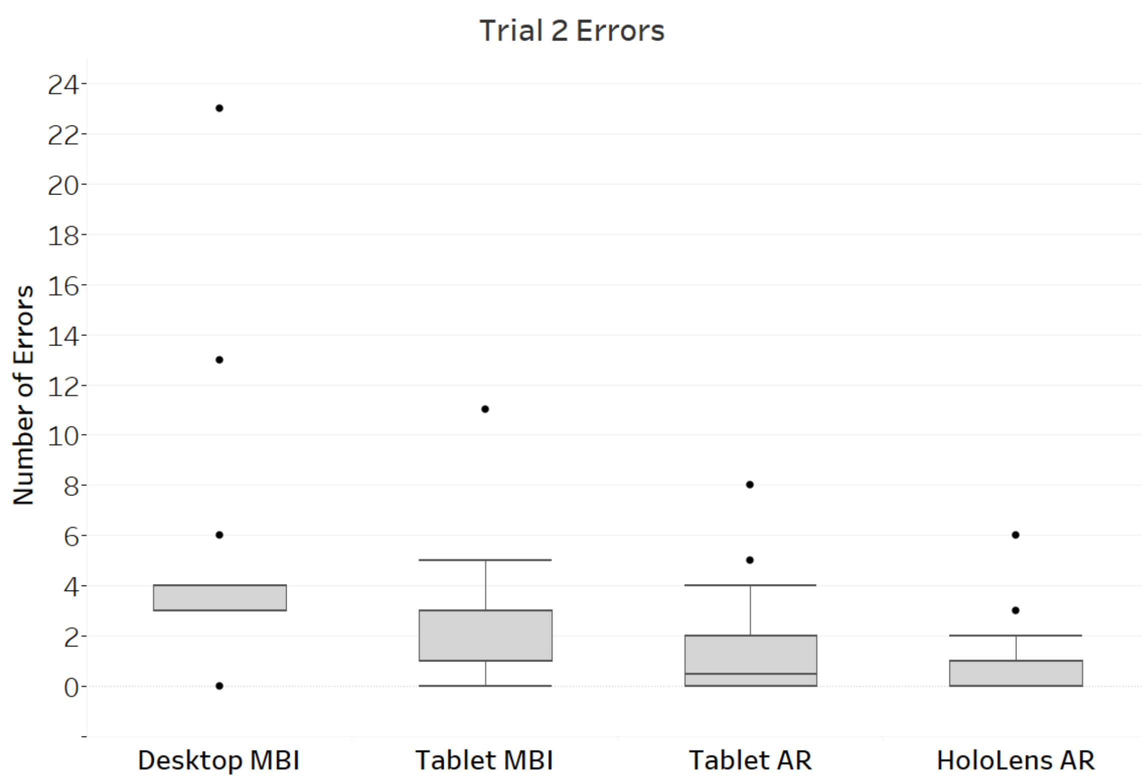

Figure 9. Bar charts of Trial 2 errors.

errors for the groups $\chi^2(3) = 29.303$, $p < .0005$. The subsequent pairwise comparison revealed that there was, once again, a significant difference between the median errors for the HoloLens AR (*Mdn* = 0.0) and the Tablet MBI (*Mdn* = 1.0) ($p = .025$) and the HoloLens and Desktop MBI (*Mdn* = 4.0) ($p < .0005$). The median number of errors for tablet AR condition (*Mdn* = 0.5) was also significantly different than that of the Desktop MBI (*Mdn* = 4.0) ($p < .0005$).

Completion Time

For Trial 1, a Kruskal-Wallis test was conducted to determine if there were differences in the completion times of the four instructional conditions: “Desktop MBI” (n=13), “Tablet MBI” (n=15), “Tablet AR” (n=40), and “HoloLens AR” (n=35). Box plots of the Trial 1 times in Figure 10 show that the four groups had somewhat similar distributions. A Kruskal-Wallis test showed that there was a significant difference in median completion times for the four groups $\chi^2(3) = 25.990$, $p < .0005$. Next, a pairwise comparison using Dunn’s procedure and a Bonferroni correction was used to determine if a significant difference was present between specific groups. This post hoc test showed that there was a significant difference between the median completion time for the HoloLens AR (*Mdn* = 1328 s) and Tablet AR (*Mdn* = 1572 s) ($p = .004$), HoloLens and Tablet MBI (*Mdn* = 1801 s) (p =.001), and the HoloLens and Desktop MBI (*Mdn* = 1868 s) ($p < .0005$).

Trial 2 yielded different results, shown by the box plots in Figure 11. The Kruskal-Wallis test determined that there was a statistically significant difference between these median completion times $\chi^2(3) = 12.364$, $p = .006$. The post hoc test showed that the only conditions which were significantly different were the HoloLens AR (*Mdn* = 1026 s) and

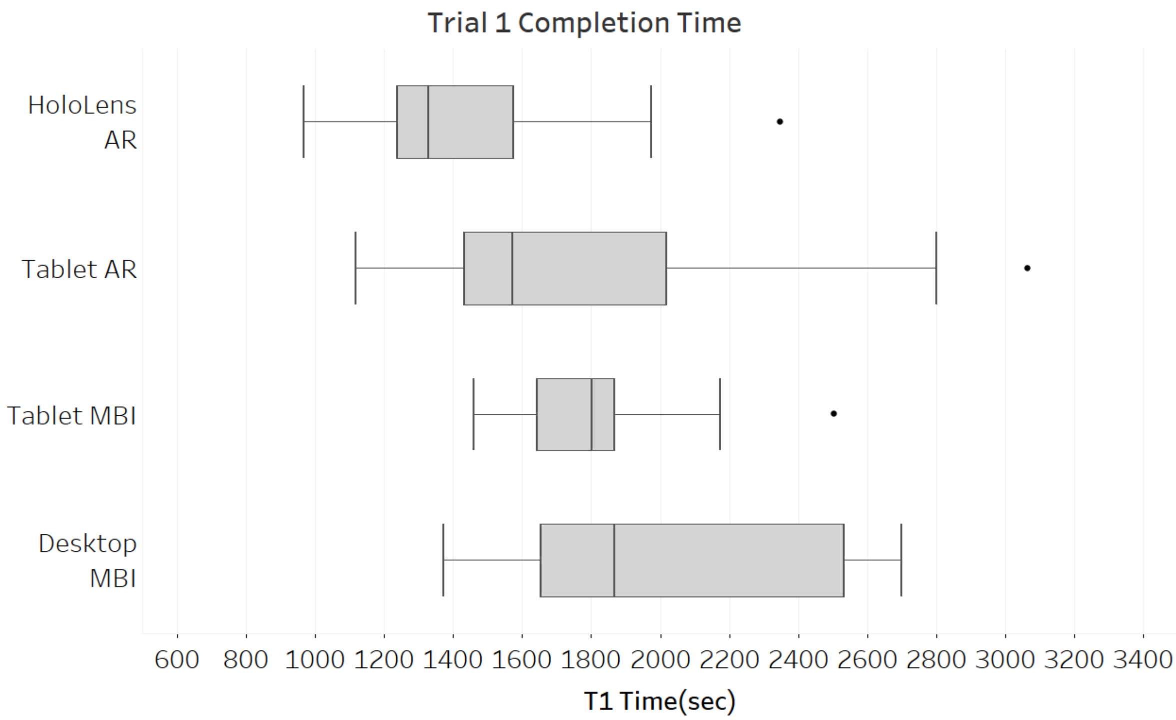

Figure 10. Box plots of Trial 1 completion times.

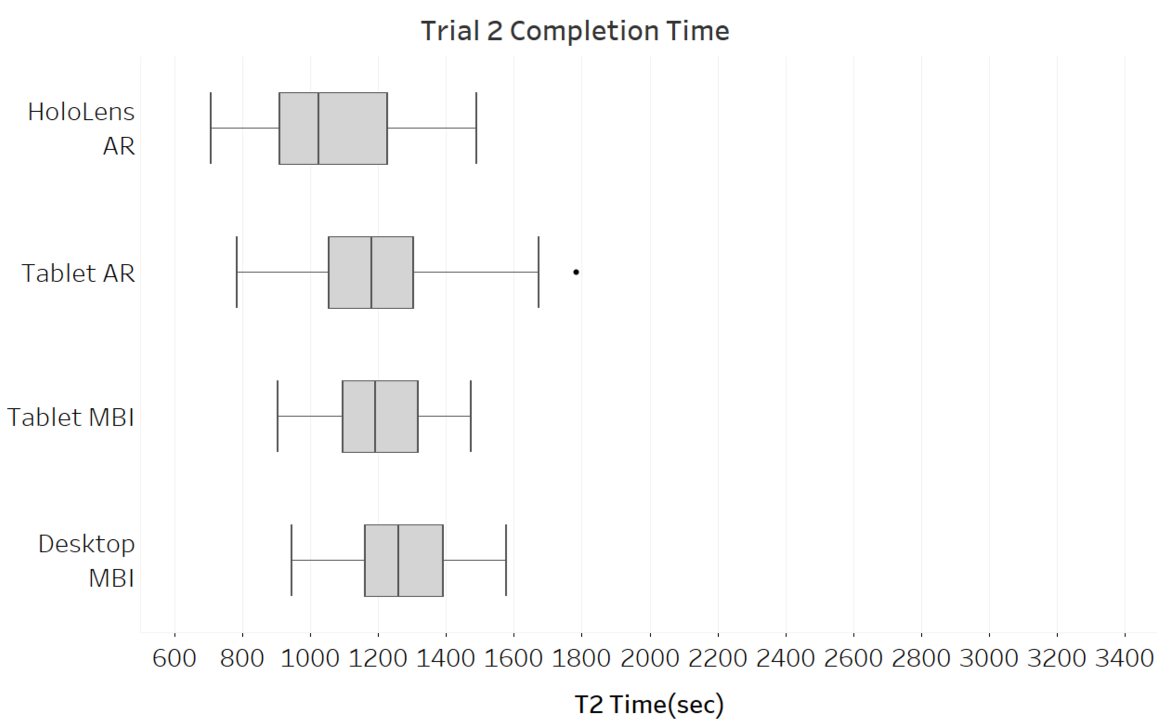

Figure 11. Box plots of Trial 2 completion times.

the Desktop MBI conditions (*Mdn* = 1259 s) (p = .013). The Tablet AR (*Mdn* = 1182 s) and Tablet MBI (*Mdn* = 1193 s) conditions were not significantly different from the other groups.

Net Promoter Score

The NPS is used to gauge how likely a user would be to recommend a product or service to a friend. In this case, the participant's answers were given on a five-point scale. When calculating the NPS, responses of 1, 2, and 3 were considered detractors (people unlikely to recommend). Participants who chose 5 were considered promoters. To calculate the NPS, the total detractors were subtracted from the total number of promoters and divided by the number of samples. It is possible to have a NPS ranging between -100 and 100%. A typical NPS for a large company is around 16% (Reichheld, 2003). So, while the scale allows higher scores, they are less uncommon.

According to this calculation, the highest NPS resulted from the tablet AR condition (53%) followed by the HoloLens AR condition (14%). NPS results of both MBI conditions were negative, meaning that these conditions had more detractors than promoters. The NPS scores of the tablet AR and desktop MBI conditions were -31% and -20%, respectively.

Qualitative Data

Study participants were asked to provide qualitative feedback at the end of the study regarding their experience with the work instructions. The goal of this section was to further understand user's attitudes towards the use of the new HoloLens device for assembly applications. Therefore, this section will focus specifically on those comments given by the participants who used the Microsoft HoloLens AR instructions.

Of the 35 participants who used the HoloLens AR instructions, 26% mentioned problems with the 3D tracking or registration of virtual images with the real environment. 14% of participants mentioned that the HoloLens was heavy or uncomfortable to wear during the study. Another 11% suggested that having the AR graphics constantly in their field of view was distracting or annoying.

Many participants had positive feedback as well. 29% of the HoloLens participants mentioned that they thought the HoloLens AR instructions were easy to use and 11% said that it was easier to use than a paper manual. Lastly, 11% of the surveyed participants reported that they felt the HoloLens AR instructions reduced their mental work load in some way.

Discussion

For this experiment, four different instructional conditions were evaluated on measures of human performance as well as the users' opinion of the instructional tool. This data was used to provide insight into the effect of using the Microsoft HoloLens to provide assembly instructions.

Based on the results comparing the median completion times and error rates, the HoloLens AR condition resulted in better overall human performance on the assembly task than both non-AR conditions. This result is analogous to the results shown in previous research studies that compared AR assembly instructions to traditional, 2D assembly instructions.

Despite the significant difference in median errors between the HoloLens AR and the two non-AR conditions, no significant difference in errors was found between the HoloLens AR and Tablet AR conditions. However, by examining the boxplots of error data

(Figure 8 and Figure 9), it is clear that the data was subject to a floor effect that could be causing the similarity in error rates. Therefore, the results are inconclusive in indicating which of the AR conditions resulted in fewer errors. A follow-up study could be conducted using a more complicated assembly task to eliminate the floor effect and further investigate the effects that different AR hardware have on assembly errors.

The HoloLens AR group performed the assembly task faster than all other groups in Trial 1, including the Tablet AR condition. Overall, median completion time for Trial 1 when using the HoloLens was 16% faster than the Tablet AR group, 26% faster than the Tablet MBI group, and 29% faster than the Desktop MBI group. This represents a significant time savings over traditional non-AR instructions as well as Tablet AR instructions. This result is also supported by the qualitative feedback in which many of the participants mentioned they thought the HoloLens instructions seemed very efficient. Trial 2 was less conclusive, showing only that the HoloLens condition yielded faster times than the desktop condition. However, since the users were exposed to two identical tasks, the Trial 2 results are likely due to learning effects. Overall, the HoloLens instructions resulted in faster first-time assemblies than the other conditions. Some of this time savings could be attributed to the constant presence of the HoloLens instructions which prevents users from having to spend time traveling between the instructions and the work area.

Despite many positive comments from the HoloLens users, the HMD had an NPS of 11%. Although close to the industry average of 16% (Reichheld, 2003), this was much lower than the NPS of the Tablet AR instructions (53%). One reason for this difference could be the time elapsed between the recording of the Tablet AR data and the HoloLens AR data. During the interim period of about two years, AR applications for mobile devices, such as Pokémon Go, became more popular, possibly desensitizing users to the novelty of AR. Additionally, some of the qualitative feedback, described in the following paragraph, may have also contributed to the lower NPS. However, the HoloLens NPS was still higher than those of the Tablet MBI and Desktop MBI conditions, both of which had more detractors than promoters, making the HoloLens AR instructions a preferable alternative to traditional, 2D assembly instructions.

Some of the comments from the qualitative results suggest that the HoloLens device still has some limitations. For example, many participants mentioned that the position of the virtual objects did not align correctly with the assembly parts. However, the low error rate and significantly faster completion times observed by HoloLens users contradict this feedback and showed that any tracking errors which may have been present did not negatively affect their ability to perform the task quickly and accurately. Additionally, some users found that the headset was uncomfortable to wear for the duration of the task, and that the instructions sometimes obstructed their view when assembling parts.

Conclusion

The research presented in this paper sought to expand upon previous work which demonstrated the advantages of AR technology for guided assembly tasks. Specifically, this paper investigated benefits to human performance when using the new Microsoft HoloLens HMD for a realistic manufacturing assembly task. The between-subjects user study showed that using the Microsoft HoloLens AR instructions led to significantly fewer errors and faster overall assembly times by as much as 15% when compared to AR instruction presented on a Tablet. However, fewer users reported willingness to promote the HoloLens technology. Feedback from the users indicated that some changes could be made to improve the user experience, such as toggling the AR overlay on and off, to improve visibility for close-up tasks.

This research shows that AR guided assembly instructions presented via a modern optical see-through HMD, like the Microsoft HoloLens, can be better alternative than tablet AR instructions (and traditional 2D instructions) for large-scale assembly tasks, especially when mobility is important to the assembly process. This is because the use of HMD instructions, as opposed to Tablet AR and 2D methods, can reduce assembly times while maintaining, and in some cases, improving assembly accuracy.

References

Azuma, R. (1997). A survey of augmented reality. *Presence: Teleoperators and Virtual Environments*, *6*(4), 355–385. https://doi.org/10.1.1.30.4999

Azuma, R., Baillot, Y., & Behringer, R. (2001). Recent advances in augmented reality. *Computer Graphics*. Retrieved from http://ieeexplore.ieee.org/xpls/abs_all.jsp?arnumber=963459

Baird, K. M., & Barfield, W. (1999). Evaluating the effectiveness of augmented reality displays for a manual assembly task. *Virtual Reality*, *4*(4), 250–259. https://doi.org/10.1007/BF01421808

Biocca, F. A., & Rolland, J. P. (1998). Virtual Eyes Can Rearrange Your Body: Adaptation to Visual Displacement in See-Through, Head-Mounted Displays. *Presence: Teleoperators*, *7*(3), 262–277. https://doi.org/10.1162/105474698565703

Blattgerste, J., Strenge, B., Renner, P., Pfeiffer, T., & Essig, K. (2017). Comparing Conventional and Augmented Reality Instructions for Manual Assembly Tasks. In *Proceedings of the 10th International Conference on PErvasive Technologies Related to Assistive Environments - PETRA '17* (pp. 75–82). https://doi.org/10.1145/3056540.3056547

Boeing. (2018). Boeing Tests Augmented Reality in the Factory. Retrieved February 28, 2018, from http://www.boeing.com/features/2018/01/augmented-reality-01-18.page

Boud, A., Haniff, D., Baber, C., & Steiner, S. J. (1999). Virtual reality and augmented reality as a training tool for assembly tasks. *IEEE International Conference on Information Visualization*, 32–36.

Caudell, T. P., & Mizell, D. W. (1992). Augmented reality: an application of heads-up display technology to manual manufacturing processes. In *Proceedings of the Twenty-Fifth Hawaii International Conference on System Sciences* (pp. 659–669 vol.2). Ieee. https://doi.org/10.1109/HICSS.1992.183317

Cuervo, E., & Eduardo. (2017). BEYOND REALITY. *GetMobile: Mobile Computing and Communications*, *21*(2), 9–15. https://doi.org/10.1145/3131214.3131218

DAQRI Smart Glasses. (2018). Retrieved March 30, 2018, from https://www.daqri.com/products/smart-glasses/

De Crescenzio, F., Fantini, M., Persiani, F., Di Stefano, L., Azzari, P., & Salti, S. (2011). Augmented reality for aircraft maintenance training and operations support. *IEEE Computer Graphics and Applications*, *31*(1), 96–101. https://doi.org/10.1109/MCG.2011.4

Echtler, F., Sturm, F., Kindermann, K., Klinker, G., Stilla, J., Trilk, J., & Najafi, H. (2004). The intelligent welding gun: Augmented reality for experimental vehicle construction. In *Virtual and Augmented Reality Applications in Manufacturing* (pp. 333–360). London: Springer London. https://doi.org/10.1007/978-1-4471-3873-0_17

Feiner, S., Macintyre, B., & Seligmann, D. (1993). Knowledge-based augmented reality. *Communications of the ACM*, *36*(7), 53–62. https://doi.org/10.1145/159544.159587

Funk, M., Kosch, T., Greenwald, S. W., & Schmidt, A. (2015). A benchmark for interactive augmented reality instructions for assembly tasks. In *Proceedings of the 14th International Conference on Mobile and Ubiquitous Multimedia - MUM '15* (pp. 253–257). New York, New York, USA: ACM Press. https://doi.org/10.1145/2836041.2836067

Funk, M., Kosch, T., & Schmidt, A. (2016). Interactive worker assistance: comparing the effects of in-situ projection, head-mounted displays, tablet, and paper instructions. In *Proceedings of the 2016 ACM International Joint Conference on Pervasive and Ubiquitous Computing* (pp. 934–939). New York, New York, USA: ACM. https://doi.org/10.1145/2971648.2971706

Henderson, S., & Feiner, S. (2009). Evaluating the benefits of augmented reality for task localization in maintenance of an armored personnel carrier turret. *Mixed and Augmented Reality, 2009.* Retrieved from http://ieeexplore.ieee.org/xpls/abs_all.jsp?arnumber=5336486

Henderson, S., & Feiner, S. (2011). Augmented reality in the psychomotor phase of a procedural task. In *2011 10th IEEE International Symposium on Mixed and Augmented Reality* (pp. 191–200). IEEE. https://doi.org/10.1109/ISMAR.2011.6092386

Hoover, M., MacAllister, A., Holub, J., Gilbert, S., Winer, E., & Davies, P. (2016). Assembly Training Using Commodity Physiological Sensors. In *Interservice/Industry Training, Simulation, and Education Conference (I/ITSEC)*.

Hou, L., Wang, X., & Truijens, M. (2015). Using Augmented Reality to Facilitate Piping Assembly: An Experiment-Based Evaluation. *Journal of Computing in Civil Engineering*, *29*(1), 5014007. https://doi.org/10.1061/(ASCE)CP.1943-5487.0000344

Liao, T., & Humphreys, L. (2015). Layar-ed places: Using mobile augmented reality to tactically reengage, reproduce, and reappropriate public space. *New Media & Society*, *17*(9), 1418–1435. https://doi.org/10.1177/1461444814527734

Loch, F., Quint, F., & Brishtel, I. (2016). Comparing video and augmented reality assistance in manual assembly. In *Proceedings - 12th International Conference on Intelligent Environments, IE 2016* (pp. 147–150). https://doi.org/10.1109/IE.2016.31

Macallister, A., Gilbert, S., Holub, J., Winer, E., & Davies, P. (2016). Comparison of Navigation Methods in Augmented Reality Guided Assembly. *Interservice/Industry Training, Simulation, and Education Conference (I/ITSEC)*, 1–14.

MacAllister, A., Hoover, M., Gilbert, S., Oliver, J., Radkowski, R., Garrett, T., … Davies, P. (2017). Comparing Visual Assembly Aids for Augmented Reality Work Instructions. In *Interservice/Industry Training, Simulation, and Education Conference (I/ITSEC)*.

Meta Augmented Reality. (2017). Retrieved March 30, 2018, from http://www.metavision.com/

Microsoft. (n.d.). Install the tools - Mixed Reality | Microsoft Docs. Retrieved April 4, 2018, from https://docs.microsoft.com/en-us/windows/mixed-reality/install-the-tools#mixed-reality-toolkit

Microsoft. (2018). Why HoloLens. Retrieved February 26, 2018, from https://www.microsoft.com/en-us/hololens/why-hololens

Nee, A. Y. C., Ong, S. K., Chryssolouris, G., & Mourtzis, D. (2012). Augmented reality applications in design and manufacturing. *CIRP Annals - Manufacturing Technology*, *61*(2), 657–679. https://doi.org/10.1016/j.cirp.2012.05.010

Neumann, U., & Majoros, A. (1998). Cognitive, performance, and systems issues for augmented reality applications in manufacturing and maintenance. *Proceedings. IEEE 1998 Virtual Reality Annual International Symposium (Cat. No.98CB36180)*, 4–11. https://doi.org/10.1109/VRAIS.1998.658416

Nilsson, S., & Johansson, B. (2007). Fun and usable. In *Proceedings of the 2007 conference of the computer-human interaction special interest group (CHISIG) of Australia on Computer-human interaction: design: activities, artifacts and environments - OZCHI '07* (p. 123). New York, New York, USA: ACM Press. https://doi.org/10.1145/1324892.1324915

Palmarini, R., Erkoyuncu, J. A., Roy, R., & Torabmostaedi, H. (2018). A systematic review of augmented reality applications in maintenance. *Robotics and Computer-Integrated Manufacturing*, *49*, 215–228. https://doi.org/10.1016/J.RCIM.2017.06.002

Reichheld, F. (2003). The one number you need to grow. *Harvard Business Review*, *81*(12), 46–54.

Richardson, T., Gilbert, S., Holub, J., Macallister, A., Radkowski, R., Davies, P., & Terry, S. (2014). Fusing Self-Reported and Sensor Data from Mixed-Reality Training. *I/ITSEC*, (14158), 1–12. Retrieved from http://www.fredericktt.com/pubs/iitsec2014.pdf

Sanna, A., Manuri, F., Lamberti, F., Member, S., Paravati, G., & Pezzolla, P. (2015). Using Handheld Devices to Support Augmented Reality-based Maintenance and Assembly Tasks. *IEEE International Conference on Consumer Electronics (ICCE) Using*, 178–179. https://doi.org/10.1109/ICCE.2015.7066370

Syberfeldt, A., Danielsson, O., & Holm, M. (2015). Visual Assembling Guidance Using Augmented Reality. *Procedia Manufacturing*, *1*, 98–109. https://doi.org/10.1016/J.PROMFG.2015.09.068

Tang, A., Owen, C., Biocca, F., & Mou, W. (2003). Comparative Effectiveness of Augmented Reality in Object Assembly. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems* (pp. 73–80).

Tatić, D., & Tešić, B. (2017). The application of augmented reality technologies for the improvement of occupational safety in an industrial environment. *Computers in Industry*, *85*, 1–10. https://doi.org/10.1016/j.compind.2016.11.004

Träskbäack, M., & Haller, M. (2004). Mixed reality training application for an oil refinery. In *Proceedings of the 2004 ACM SIGGRAPH international conference on Virtual Reality continuum and its applications in industry - VRCAI '04* (p. 324). New York, New York, USA: ACM Press. https://doi.org/10.1145/1044588.1044658

Unity Technologies. (n.d.). Unity. Retrieved April 4, 2018, from https://unity3d.com/

Uva, A. E., Gattullo, M., Manghisi, V. M., Spagnulo, D., Cascella, G. L., & Fiorentino, M. (2017). Evaluating the effectiveness of spatial augmented reality in smart manufacturing: a solution for manual working stations. *The International Journal of Advanced Manufacturing Technology*, *94*(1–4), 509–521. https://doi.org/10.1007/s00170-017-0846-4

Wickens, C., Gordon, S., Liu, Y., & Lee, J. (1998). An introduction to human factors engineering. Retrieved from http://www.academia.edu/download/44059426/WickensEtAl-HFE-Ch4.PDF

Wiedenmaier, S., Oehme, O., Schmidt, L., & Luczak, H. (2003). Augmented reality (AR) for assembly processes design and experimental evaluation. *International Journal of Human-Computer Interaction*, *16*(3), 497–514. https://doi.org/10.1207/S15327590IJHC1603

Zheng, X. S., Foucault, C., Matos, P., Silva, D., Dasari, S., Yang, T., & Goose, S. (2015). Eye-Wearable Technology for Machine Maintenance: Effects of Display Position and Hands-free Operation. *Proceedings of the 33rd Annual ACM Conference on Human Factors in Computing Systems*, 2125–2134. https://doi.org/10.1145/2702123.2702305

CHAPTER 4. CONCLUSIONS

The research presented in this thesis sought to expand upon previous work which demonstrated the advantages of AR technology for guided assembly tasks. Specifically, this thesis investigated benefits to human performance when using the new Microsoft HoloLens HMD for a realistic manufacturing assembly task. The between-subjects user study showed that using the Microsoft HoloLens AR instructions led to significantly fewer errors and faster overall assembly times by as much as 15% when compared to AR instruction presented on a Tablet. However, fewer users reported willingness to promote the HoloLens technology. Feedback from the users indicated that some changes could be made to improve the user experience, such as toggling the AR overlay on and off, to improve visibility for close-up tasks.

This work also investigated user opinions of the new Microsoft HoloLens hardware for assembly applications. The results showed that, although the HoloLens improved performance, user opinions of the HoloLens device were not as positive as those of the AR Tablet. During the follow up questionnaire, users identified some limitations of the HoloLens device for this application including the comfort of the device, interference due to persistent graphics, and some tracking errors. However, only a small portion of the user group made these comments about the HoloLens device. Additionally, some of these limitations can be addressed with simple changes to the AR interface design. Overall, this research shows that AR guided assembly instructions presented via a modern optical see-through HMD, like the Microsoft HoloLens, can be better alternative than tablet AR instructions (and traditional 2D instructions) for large-scale assembly tasks, especially when mobility is important to the assembly process. This is because the use of HMD instructions, as opposed to Tablet AR and 2D methods, can reduce assembly times while maintaining, and in some cases improving, assembly accuracy.

CHAPTER 5. FUTURE WORK

The priority for future work is to address the limitations listed by some of the HoloLens users and to determine causation of the low HoloLens NPS score. For example, allowing users to toggle the AR interface off and on may eliminate the visual interference some users experienced when assembling parts. Although the form factor of the HoloLens cannot be easily changed to improve comfort, more attention can be paid to ensuring the user is correctly adjusting the device to fit their head. With these improvements, continued user testing of the HoloLens can be conducted to understand if the listed limitations were, in fact, the cause of the lower HoloLens NPS score reported earlier.

Additionally, it is important to keep this work up to date by continuing to investigate new AR hardware devices as they come to market. By doing this, the manufacturing industry can continue to make informed decisions about the implementation of AR in factory settings. Additionally, continuing this research in a real factory environment would add even more merit to the conclusions outlined in this thesis. By testing different AR hardware solutions in a factory environment, the effects of environmental factors such as noise, collaboration, and safety hazards can be accounted for and measured.

REFERENCES

Abramovici, M., Wolf, M., Adwernat, S., & Neges, M. (2017). Context-aware Maintenance Support for Augmented Reality Assistance and Synchronous Multi-user Collaboration. *Procedia CIRP*, *59*, 18–22. https://doi.org/10.1016/J.PROCIR.2016.09.042

Aromaa, S., Aaltonen, I., Kaasinen, E., Elo, J., & Parkkinen, I. (2016). Use of wearable and augmented reality technologies in industrial maintenance work. In *Proceedings of the 20th International Academic Mindtrek Conference on - AcademicMindtrek '16* (pp. 235–242). New York, New York, USA: ACM Press. https://doi.org/10.1145/2994310.2994321

Azuma, R. (1997). A survey of augmented reality. *Presence: Teleoperators and Virtual Environments*, *6*(4), 355–385. https://doi.org/10.1.1.30.4999

Azuma, R., Baillot, Y., & Behringer, R. (2001). Recent advances in augmented reality. *Computer Graphics*. Retrieved from http://ieeexplore.ieee.org/xpls/abs_all.jsp?arnumber=963459

Baird, K. M., & Barfield, W. (1999). Evaluating the effectiveness of augmented reality displays for a manual assembly task. *Virtual Reality*, *4*(4), 250–259. https://doi.org/10.1007/BF01421808

Biocca, F. A., & Rolland, J. P. (1998). Virtual Eyes Can Rearrange Your Body: Adaptation to Visual Displacement in See-Through, Head-Mounted Displays. *Presence: Teleoperators*, *7*(3), 262–277. https://doi.org/10.1162/105474698565703

Blattgerste, J., Strenge, B., Renner, P., Pfeiffer, T., & Essig, K. (2017). Comparing Conventional and Augmented Reality Instructions for Manual Assembly Tasks. In *Proceedings of the 10th International Conference on PErvasive Technologies Related to Assistive Environments - PETRA '17* (pp. 75–82). https://doi.org/10.1145/3056540.3056547

Boud, A., Haniff, D., Baber, C., & Steiner, S. J. (1999). Virtual reality and augmented reality as a training tool for assembly tasks. *IEEE International Conference on Information Visualization*, 32–36.

Caudell, T. P., & Mizell, D. W. (1992). Augmented reality: an application of heads-up display technology to manual manufacturing processes. In *Proceedings of the Twenty-Fifth Hawaii International Conference on System Sciences* (pp. 659–669 vol.2). Ieee. https://doi.org/10.1109/HICSS.1992.183317

Chi, H.-L. (2013). Research trends and opportunities of augmented reality applications in architecture, engineering, and construction. *Automation in Construction*, *33*, 116–122. https://doi.org/10.1016/J.AUTCON.2012.12.017

Chimienti, V., Iliano, S., Dassisti, M., Dini, G., & Failli, F. (2010). Guidelines for implementing augmented reality procedures in assisting assembly operations. *IFIP Advances in Information and Communication Technology*, *315*, 174–179. https://doi.org/10.1007/978-3-642-11598-1_20

De Crescenzio, F., Fantini, M., Persiani, F., Di Stefano, L., Azzari, P., & Salti, S. (2011). Augmented reality for aircraft maintenance training and operations support. *IEEE Computer Graphics and Applications*, *31*(1), 96–101. https://doi.org/10.1109/MCG.2011.4

Dini, G., & Mura, M. D. (2015). Application of Augmented Reality Techniques in Through-life Engineering Services. *Procedia CIRP*, *38*, 14–23. https://doi.org/10.1016/j.procir.2015.07.044

Doshi, A., Smith, R. T., Thomas, B. H., & Bouras, C. (2017). Use of projector based augmented reality to improve manual spot-welding precision and accuracy for automotive manufacturing. *The International Journal of Advanced Manufacturing Technology*, *89*(5–8), 1279–1293. https://doi.org/10.1007/s00170-016-9164-5

Echtler, F., Sturm, F., Kindermann, K., Klinker, G., Stilla, J., Trilk, J., & Najafi, H. (2004). The intelligent welding gun: Augmented reality for experimental vehicle construction. In *Virtual and Augmented Reality Applications in Manufacturing* (pp. 333–360). London: Springer London. https://doi.org/10.1007/978-1-4471-3873-0_17

Fiorentino, M., Uva, A. E., Gattullo, M., Debernardis, S., & Monno, G. (2014). Augmented reality on large screen for interactive maintenance instructions. *Computers in Industry*, *65*(2), 270–278. https://doi.org/10.1016/J.COMPIND.2013.11.004

Friedrich, W. (2002). ARVIKA-augmented reality for development, production and service. *Proceedings. International Symposium on Mixed and Augmented Reality*, 3–4. https://doi.org/10.1109/ISMAR.2002.1115059

Funk, M., Kosch, T., Greenwald, S. W., & Schmidt, A. (2015). A benchmark for interactive augmented reality instructions for assembly tasks. In *Proceedings of the 14th International Conference on Mobile and Ubiquitous Multimedia - MUM '15* (pp. 253–257). New York, New York, USA: ACM Press. https://doi.org/10.1145/2836041.2836067

Funk, M., Kosch, T., & Schmidt, A. (2016). Interactive worker assistance: comparing the effects of in-situ projection, head-mounted displays, tablet, and paper instructions. In *Proceedings of the 2016 ACM International Joint Conference on Pervasive and Ubiquitous Computing* (pp. 934–939). New York, New York, USA: ACM. https://doi.org/10.1145/2971648.2971706

Funk, M., Mayer, S., Nistor, M., & Schmidt, A. (2016). Mobile In-Situ Pick-by-Vision. In *Proceedings of the 9th ACM International Conference on PErvasive Technologies Related to Assistive Environments - PETRA '16* (pp. 1–4). New York, New York, USA: ACM Press. https://doi.org/10.1145/2910674.2910730

Gavish, N., Gutiérrez, T., & Webel, S. (2013). Evaluating virtual reality and augmented reality training for industrial maintenance and assembly tasks. *Interactive Learning Environments*. Retrieved from http://www.tandfonline.com/doi/abs/10.1080/10494820.2013.815221

Goose, S., Sudarsky, S., Xiang Zhang, & Navab, N. (2003). Speech-enabled augmented reality supporting mobile industrial maintenance. *IEEE Pervasive Computing*, *2*(1), 65–70. https://doi.org/10.1109/MPRV.2003.1186727

Henderson, S., & Feiner, S. (2009). Evaluating the benefits of augmented reality for task localization in maintenance of an armored personnel carrier turret. *Mixed and Augmented Reality, 2009.* Retrieved from http://ieeexplore.ieee.org/xpls/abs_all.jsp?arnumber=5336486

Hořejší, P. (2015). Augmented Reality System for Virtual Training of Parts Assembly. *Procedia Engineering*, *100*, 699–706. https://doi.org/10.1016/J.PROENG.2015.01.422

Hou, L., Wang, X., & Truijens, M. (2015). Using Augmented Reality to Facilitate Piping Assembly: An Experiment-Based Evaluation. *Journal of Computing in Civil Engineering*, *29*(1), 5014007. https://doi.org/10.1061/(ASCE)CP.1943-5487.0000344

Khuong, B. M., Kiyokawa, K., Miller, A., La Viola, J. J., Mashita, T., & Takemura, H. (2014). The effectiveness of an AR-based context-aware assembly support system in object assembly. In *2014 IEEE Virtual Reality (VR)* (pp. 57–62). IEEE. https://doi.org/10.1109/VR.2014.6802051

Lamberti, F., Manuri, F., Sanna, A., Paravati, G., Pezzolla, P., & Montuschi, P. (2014). Challenges, opportunities, and future trends of emerging techniques for augmented reality-based maintenance. *IEEE Transactions on Emerging Topics in Computing*, *2*(4), 411–421. https://doi.org/10.1109/TETC.2014.2368833

Loch, F., Quint, F., & Brishtel, I. (2016). Comparing video and augmented reality assistance in manual assembly. In *Proceedings - 12th International Conference on Intelligent Environments, IE 2016* (pp. 147–150). https://doi.org/10.1109/IE.2016.31

Marner, M. R., Irlitti, A., & Thomas, B. H. (2013). Improving procedural task performance with Augmented Reality annotations. In *2013 IEEE International Symposium on Mixed and Augmented Reality (ISMAR)* (pp. 39–48). IEEE. https://doi.org/10.1109/ISMAR.2013.6671762

Martinetti, A., Rajabalinejad, M., & Van Dongen, L. (2017). Shaping the Future Maintenance Operations: Reflections on the Adoptions of Augmented Reality Through Problems and Opportunities. *Procedia CIRP*, *59*, 14–17. https://doi.org/10.1016/j.procir.2016.10.130

Milgram, P., Takemura, H., Utsumi, A., & Kishino, F. (1995). Augmented reality: a class of displays on the reality-virtuality continuum. In H. Das (Ed.), *Telemanipulator and telepresence technologies* (Vol. 2351, pp. 282–293). International Society for Optics and Photonics. https://doi.org/10.1117/12.197321

Mura, M. D., Dini, G., & Failli, F. (2016). An Integrated Environment Based on Augmented Reality and Sensing Device for Manual Assembly Workstations. *Procedia CIRP*, *41*, 340–345. https://doi.org/10.1016/J.PROCIR.2015.12.128

Nee, A. Y. C., & Ong, S. K. (2013). Virtual and Augmented Reality Applications in Manufacturing. *IFAC Proceedings Volumes*, *46*(9), 15–26. https://doi.org/10.3182/20130619-3-RU-3018.00637

Neumann, U., & Majoros, A. (1998). Cognitive, performance, and systems issues for augmented reality applications in manufacturing and maintenance. *Proceedings. IEEE 1998 Virtual Reality Annual International Symposium (Cat. No.98CB36180)*, 4–11. https://doi.org/10.1109/VRAIS.1998.658416

Nilsson, S., & Johansson, B. (2007). Fun and usable. In *Proceedings of the 2007 conference of the computer-human interaction special interest group (CHISIG) of Australia on Computer-human interaction: design: activities, artifacts and environments - OZCHI '07* (p. 123). New York, New York, USA: ACM Press. https://doi.org/10.1145/1324892.1324915

Ockerman, J. J., & Pritchett, a. R. (1998). Preliminary investigation of wearable computers for task guidance in aircraft inspection. In *IEEE Proceedings of the 2nd International Symposium on Wearable Computers* (pp. 33–41). IEEE Comput. Soc. https://doi.org/10.1109/ISWC.1998.729527

Ong, S. K., Yuan, M. L., & Nee, A. Y. C. (2008). Augmented reality applications in manufacturing: a survey. *International Journal of Production Research*, *46*(10), 2707–2742. https://doi.org/10.1080/00207540601064773

Palmarini, R. (2017). An Innovative Process to Select Augmented Reality (AR) Technology for Maintenance. *Procedia CIRP*, *59*, 23–28. https://doi.org/10.1016/J.PROCIR.2016.10.001

Palmarini, R., Erkoyuncu, J. A., Roy, R., & Torabmostaedi, H. (2018). A systematic review of augmented reality applications in maintenance. *Robotics and Computer-Integrated Manufacturing*, *49*, 215–228. https://doi.org/10.1016/J.RCIM.2017.06.002

Radkowski, R., Herrema, J., & Oliver, J. (2015). Augmented Reality-Based Manual Assembly Support With Visual Features for Different Degrees of Difficulty. *International Journal of Human-Computer Interaction, 31*(5), 337–349. https://doi.org/10.1080/10447318.2014.994194

Regenbrecht, H., Baratoff, G., & Wilke, W. (2005). Augmented reality projects in the automotive and aerospace industries. *IEEE Computer Graphics and Applications, 25*(6), 48–56. https://doi.org/10.1109/MCG.2005.124

Renner, P., & Pfeiffer, T. (2017). Attention guiding techniques using peripheral vision and eye tracking for feedback in augmented-reality-based assistance systems. In *2017 IEEE Symposium on 3D User Interfaces (3DUI)* (pp. 186–194). IEEE. https://doi.org/10.1109/3DUI.2017.7893338

Rodriguez, L., Quint, F., Gorecky, D., Romero, D., & Siller, H. R. (2015). Developing a Mixed Reality Assistance System Based on Projection Mapping Technology for Manual Operations at Assembly Workstations. *Procedia Computer Science, 75*, 327–333. https://doi.org/10.1016/J.PROCS.2015.12.254

Rogers, E. M. (2003). *Diffusion of Innovations, 5th Edition.* Free Press.

Rolland, J. P., & Fuchs, H. (2000). Optical Versus Video See-Through Head-Mounted Displays in Medical Visualization. *Presence: Teleoperators and Virtual Environments*, *9*(3), 287–309. https://doi.org/10.1162/105474600566808

Sanna, A., Manuri, F., Lamberti, F., Member, S., Paravati, G., & Pezzolla, P. (2015). Using Handheld Devices to Support Augmented Reality-based Maintenance and Assembly Tasks. *IEEE International Conference on Consumer Electronics (ICCE) Using*, 178–179. https://doi.org/10.1109/ICCE.2015.7066370

Schwerdtfeger, B., & Klinker, G. (2008). Supporting order picking with Augmented Reality. In *2008 7th IEEE/ACM International Symposium on Mixed and Augmented Reality* (pp. 91–94). IEEE. https://doi.org/10.1109/ISMAR.2008.4637331

Siegel, J., & Bauer, M. (1997). A field usability evaluation of a wearable system. *Digest of Papers. First International Symposium on Wearable Computers*, (1), 18–22. https://doi.org/10.1109/ISWC.1997.629914

Syberfeldt, A., Danielsson, O., & Holm, M. (2015). Visual Assembling Guidance Using Augmented Reality. *Procedia Manufacturing*, *1*, 98–109. https://doi.org/10.1016/J.PROMFG.2015.09.068

Syberfeldt, A., Holm, M., Danielsson, O., Wang, L., & Brewster, R. L. (2016). Support Systems on the Industrial Shop-floors of the Future – Operators’ Perspective on Augmented Reality. *Procedia CIRP*, *44*, 108–113. https://doi.org/10.1016/J.PROCIR.2016.02.017

Tang, A., Owen, C., Biocca, F., & Mou, W. (2003). Comparative Effectiveness of Augmented Reality in Object Assembly. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems* (pp. 73–80).

Tatić, D., & Tešić, B. (2017). The application of augmented reality technologies for the improvement of occupational safety in an industrial environment. *Computers in Industry*, *85*, 1–10. https://doi.org/10.1016/j.compind.2016.11.004

Träskbäack, M., & Haller, M. (2004). Mixed reality training application for an oil refinery. In *Proceedings of the 2004 ACM SIGGRAPH international conference on Virtual Reality continuum and its applications in industry - VRCAI '04* (p. 324). New York, New York, USA: ACM Press. https://doi.org/10.1145/1044588.1044658

Uva, A. E., Gattullo, M., Manghisi, V. M., Spagnulo, D., Cascella, G. L., & Fiorentino, M. (2017). Evaluating the effectiveness of spatial augmented reality in smart manufacturing: a solution for manual working stations. *The International Journal of Advanced Manufacturing Technology*, *94*(1–4), 509–521. https://doi.org/10.1007/s00170-017-0846-4

Wang, X., Ong, S. K., & Nee, A. Y. C. (2016). Multi-modal augmented-reality assembly guidance based on bare-hand interface. *Advanced Engineering Informatics*, *30*(3). https://doi.org/10.1016/j.aei.2016.05.004

Weaver, K. A., Baumann, H., Starner, T., Iben, H., & Lawo, M. (2010). An empirical task analysis of warehouse order picking using head-mounted displays. In *Proceedings of the 28th international conference on Human factors in computing systems - CHI '10* (p. 1695). New York, New York, USA: ACM Press. https://doi.org/10.1145/1753326.1753580

Webel, S., Bockholt, U., Engelke, T., Gavish, N., Olbrich, M., & Preusche, C. (2013). An augmented reality training platform for assembly and maintenance skills. *Robotics and Autonomous Systems*, *61*(4), 398–403. https://doi.org/10.1016/J.ROBOT.2012.09.013

Westerfield, G., Mitrovic, A., & Billinghurst, M. (2015). Intelligent Augmented Reality Training for Motherboard Assembly. *International Journal of Artificial Intelligence in Education*, *25*(1), 157–172. https://doi.org/10.1007/s40593-014-0032-x

Wickens, C., Gordon, S., Liu, Y., & Lee, J. (1998). An introduction to human factors engineering. Retrieved from http://www.academia.edu/download/44059426/WickensEtAl-HFE-Ch4.PDF

Wiedenmaier, S., Oehme, O., Schmidt, L., & Luczak, H. (2003). Augmented reality (AR) for assembly processes design and experimental evaluation. *International Journal of Human-Computer Interaction*, *16*(3), 497–514. https://doi.org/10.1207/S15327590IJHC1603

Yeh, K.-C., Tsai, M.-H., & Kang, S.-C. (2012). On-Site Building Information Retrieval by Using Projection-Based Augmented Reality. *Journal of Computing in Civil Engineering*, *26*(3), 342–355. https://doi.org/10.1061/(ASCE)CP.1943-5487.0000156

Zheng, X. S., Foucault, C., Matos, P., Silva, D., Dasari, S., Yang, T., & Goose, S. (2015). Eye-Wearable Technology for Machine Maintenance: Effects of Display Position and Hands-free Operation. *Proceedings of the 33rd Annual ACM Conference on Human Factors in Computing Systems*, 2125–2134. https://doi.org/10.1145/2702123.2702305

Zhou, J., Lee, I., Thomas, B., Menassa, R., Farrant, A., & Sansome, A. (2012). In-situ Support for Automotive Manufacturing Using Spatial Augmented Reality. *The International Journal of Virtual Reality*, *11*(1), 33–41. Retrieved from http://search.ror.unisa.edu.au/record/UNISA_ALMA51108545770001831/media/digital/open/9915909682001831/12143289090001831/13143283990001831/pdf